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DEVELOPMENTS IN THE AMERICAN PETROLEUM INDUSTRY, 1914-19

EXPLORATION, DRILLING, PRODUCTION, AND TRANSPORTATION

(A REVIEW AND DIGEST)

BY

H. C. FOWLER

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DEVELOPMENTS IN THE AMERICAN PETROLEUM INDUSTRY, 1914-19

Exploration, Drilling, Production, and Transportation[1/]

(A review and digest)

By H. C. Fowler[2/]

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BACKGROUND

Technical developments in the American petroleum industry as regards exploration, drilling, production, and transportation were characterized by many anomalous conditions during the half decade 1914-19. A review of the literature of that period discloses the striking fact that individual geologists, engineers, and other technologists were surprisingly well versed concerning the occurrence of natural hydrocarbons and methods of extracting them and were acquainted with many of the physical and chemical characteristics that influence the behavior of fluids in natural reservoirs. However, the industry as a whole knew little of the correct application of recognized fundamentals; indeed, judged by present standards certain expediencies of self-styled "practical" operators seem cumbersome, if not evidences of ignorance.

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Nevertheless, anyone reviewing this earlier era of the petroleum industry should be careful not to assume too critical an attitude because many tools and devices then in use or being evolved - although crude in appearance - were ingenious in design and relatively effective for their intended purposes. It should be remembered, too, that present-day practices and equipment, gaged by the increased knowledge of one or more decades hence, may also appear relatively crude.

In making such an appraisal a person should recognize the hazards of being unfair or of giving a biased digest by assuming that the written statements of one or a few so-called authorities represent the sum total of knowledge on a given subject. Many picturesque anecdotes have edged their way into a status of historical fact because too much credence has been given to the fables of a good story teller; this generalization applies to some extent to technical as well as popular literature. Probably the fairest way to review accurately the conditions of an earlier time is to balance, as far as possible, the statements of recognized leaders of the period against later events that can be authenticated.

With these thoughts in mind, the oil-trade publications (then relatively few) issued from 1914 to 1919 and many of the technical writings of that period have been reviewed with care. Sources of fruitful reference material have been the bibliographies of petroleum and allied substances compiled by the Federal Bureau of Mines (38)[3/] and the Petroleum and Natural Gas Bibliography by Hardwicke (82).

In this study it has been difficult to maintain proper perspective because if date lines and other identifying time bases were eliminated many of the writings of the pre-war period and that during which the United States actually was at war might seem to have been prepared for yesterday' presentation.

Still another aspect is the difficulty of drawing a sharply defining line at or about April 17, 1917 (the date of our official declaration of war) that will segregate in two categories the kaleidoscopic events of that war-torn period as they affect or are reflected by technical developments of the American petroleum industry. It is true that with the formal declaration of war human energies were strained even more than before to produce additional oil and convert it into essential products for the fleet, the American Expeditionary Force, domestic war-time activities, and the Allies. More wells were drilled on "wildcat locations," and more costly innovations were tried because the price of oil warranted such expenditures. Many persons will recall that gasolineless Sundays curtailed, if not almost stopped, pleasure driving in some areas on that customary recreational day of the week. Plans and schemes (some good, some indifferent, and others actually bad) were proposed in great number - many unsolicited - to boost production. Many more refining plants were built to meet the growing demand for gasoline

3/ Figures in parentheses refer to citations in the bibliography at the end of this report. Page references within the parentheses represent those in the citation and not in this report.

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and fuel oil (see Kraemer (104)). Wells, tank farms, pipe lines, and refineries were guarded against possible sabotage. On the whole, however, the petroleum industry went about its business with no ruffle of drums or waving of banners. When voluntary enlistment or the draft took key men from a company organization the ranks closed in, and often one man did the former work of two without complaint. It was the spirit of the period, and necessary and expected readjustments were made without fanfare.

As nearly as can be determined, in the technical fields of exploration, extraction, and transportation, the actual entrance of this country into the World War forced early introduction of relatively few innovations that affected the upward trend, already begun, of an increasing scientific knowledge and its practical applications. It is believed that most of the new techniques of the period would have evolved at about their natural rate of growth and development whether or not this country had joined the Allies.

There is probably a definite reason for this difference between the psychogenesis of human mass reactions and the evolution of scientific physical expressions taking the form of industrial methods, devices, or processes. This thought pertaining to bounding time limits has been expressed previously in reviews of technical development during designated periods. For example, the writer (67) has stated:

> The significance of newly found engineering facts and resulting new departures in economic arrangements cannot be bounded by definite calendar limits. Several years of experiment may be required to bring a newly conceived idea to satisfactory practical application, although during the development stage it may exert an influence on the industry. Even after a new idea, resulting in a method of operation, device, or tool, is proved its ultimate effect is not easy to determine because of the appreciable "time-lag" required to evaluate cause and effect properly.

Statistical Position of the Industry

To maintain a suitable outlook throughout this digest, it will be helpful to remember that the capital investment of the petroleum industry in 1914 was said to have been about one-half billion dollars, compared with what now is termed a 14-1/2-billion dollar industry, and some are inclined to place the present valuation even higher. The total crude-oil production in the United States in 1914 was only 265,763,000 barrels, compared with more than one billion barrels for recent annual production. California led all other States, with almost 100 million barrels; Oklahoma was second, with approximately 73.5 million barrels; and Illinois, with almost 22 million barrels, outranked Texas for third place by nearly 2,000,000 barrels. At the end of the war the statistical positions of the leading States had changed. The United States produced 355,928,000 barrels in 1918. Of this quantity, Oklahoma produced 103.3 million, California 97.5 million, Kansas 45.4 million, Texas 38.8 million, and Illinois had dropped to 13.4 million barrels.

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At the end of 1919 the total domestic crude-oil production was 378,367,000 barrels, California again leading with 101.2 million, while Oklahoma dropped to second place with 86.9 million barrels (but again took first place in 1920). Texas advanced to 79.4 million in 1919, Kansas dropped to 33 million, and Illinois went into a further decline with slightly less than 12 million barrels (161).

Miser and associates (129) have given a concise over-all picture of the various and varying estimates of petroleum reserves that have been made in the past. Unfortunately their curve cannot be extrapolated backward from January 1, 1922, with any assurance of accuracy. They state that the first estimate of this kind was made by David T. Day at the instance of President Theodore Roosevelt. The "spread" of Day's estimate (published in Geological Survey Bull. 394, 1909 (54) was 10 to 24-1/2 billion barrels, depending on what were considered proved and "to be discovered" productive areas. Other estimates followed, for example, that of Arnold in 1915 (8, p. 695), but lack of factual information made close approximations virtually impossible. When technologists did attempt to give a measure of available oil "in sight", their statements frequently were distorted in the press, a condition that has not changed with the years. To illustrate the perennial difference in viewpoint between technical statements and press reports, the following example may be cited: The Director of the Bureau of Mines, in an address in September 1916, stated that "at present rates (of withdrawal) the available stores of oil in sight will not last over 30 years;" news items immediately appeared in different parts of the country conveying the erroneous idea to the public that the Director of the Bureau of Mines had said the oil reserves of the United States would be exhausted in less than 30 years.

It was not until 1921 that an estimate was made in which proved reserves were separated definitely from only suspected fields. This work was done by the Geological Survey and the American Association of Petroleum Geologists. According to Miser and associates, "In this estimate, 5 billion barrels were classified as oil 'in sight' on January 1, 1922, and 4 billion barrels additional as 'prospective and possible' and recoverable by the current methods of production."

Whether the figure for known reserves during the war period may have been 5 billion barrels or less, the curves of the Geological Survey writers (129, p. 290) showing "estimates of proved reserves of petroleum plus cumulative production" and "cumulative production" have a striking parallelism until after 1925, when the reserve curve begins to have a steeper slope (rises faster) than the cumulative-production curve. These 5- to 9-billion-barrel estimates of 1922 seem small, indeed, compared with a recent estimate of nearly 20 billion barrels (146) of known reserves.[4]

4/ According to the American Petroleum Institute committee on petroleum reserves, the estimated proved petroleum reserves in the United States as of January 1, 1940, were 18,483,012,000 barrels. The committee's estimate as of January 1, 1941, was 19,024,515,000 barrels. (See Oil and Gas Jour. March 27, 1941, p. 66.)

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Status of Technology in the Industry

Technology Versus "Practical Methods"

During 1914-19 some of the present technical and executive leaders were still in grade school. Others who were attending colleges were looking forward to careers as structural, hydraulic, mining, or other kinds of engineers or were intending to enter professions far afield from the engineering pursuits of finding and extracting, transporting, and processing petroleum and natural gas.

In fact, petroleum engineers had barely established a class profession, and many who were doing production-engineering work at the early part of the period were called "technologists." The first United States Civil Service examination for "oil-recovery engineer" was held after the Armistice. So-called resident engineers of oil companies were concerned primarily with civil-engineering activities such as making surface-property maps, laying out tank grades and engine foundations, strapping tanks, erecting structures, and doing similar work. Many of them had had virtually no opportunity to study underground conditions because that work was considered a prerogative of drilling and production superintendents. The first geologists whose duties brought them to the derrick floor usually were referred to as "rock hounds" or "mud smellers" by men in the field who stressed the point (frequently incorrectly) that their own working experience made them practical.

Illustrative of the general disdain of "practical oil men" for those having technical education, it is recalled that as late as 1920 a young geologist, now professor of petroleum engineering at a well-known university, was asked by the drilling crew what he called "sand." The young geologist gave the terse and somewhat academic definition: "Sand is composed of water-worn particles." Partly in fun but more in a spirit of retaliation, the drilling crew took some steel filings, subjected them to the spray from the "mud hose" for a short time, then mixed them with shale from an adjacent outcrop, and placed the material in a sample bag which they labeled "sandy shale." Upon his next visit to the rig to inspect and collect the samples for the previous tour (pronounced "tower") the geologist realized at once that he had been "framed." Such horseplay indicates that in the petroleum industry of the pre-war period and even after the Armistice geologists and engineers had to fight their way against prejudices of those who considered "high-brow book learning" a hindering vogue rather than an asset.

This condition was not entirely the fault of those who resisted evidences of growing pains of the newer order of geological examination of formations and drilling and production techniques. Too frequently a young engineer or geologist emerged from his college commencement exercises without fully realizing what commencement actually means. The superior attitude has never been acceptable to those schooled by hard knocks. Some of the older technologists, as well as practical operators who recognized the advantages of technology in their business, sensed this condition and gave wise counsel. For example, in 1916 young geologists were publicly warned against being too optimistic regarding the outcome of their recommendations. The statement was made that most operators continued to assume

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a patronizing, semitolerant attitude toward geological work, a throw-back to the definite and strong prejudice against it.

Sometimes it is enlightening to have the viewpoint of an outsider. Such an appraisal may be refreshing, also, provided it is not too severe. Frederick A. Talbut, a Britisher, writing in April 1915, summed up the situation concisely when he stated that although skilled in drawing oil from the earth once a new deposit was found, the average American oil worker had contempt for geological deductions.

The evolution of the scientific approach to solving many knotty geological and engineering problems of the petroleum industry is illustrated better by several typical incidents in following sections of this paper, but it seems timely to note here an undertone in the technical literature shortly after this country formally joined the Allies.

Hager (78) implied a view, probably held by many, that the peak of oil production had been reached in 1915, 1916, and 1917 in Oklahoma and Kansas. Others publicly stated concern over the diminishing reserves in the Gulf Coast and other areas. In a later section it is shown that geologists in the Mid-Continent were working largely on the basis of surface geology and other surface indications, and many of the easily recognized structures had been prospected with the drill. Hager believed that deeper pay horizons would be found in many areas and that some fields would be extended, but a significant part of his paper is the statement: "* * * the period of intensive development has now arrived." He urged that the techniques of petroleum engineering be utilized fully and that every engineer try to convince oil operators that combined engineering and geological methods were requisite to the intensive development of oil properties then in prospect. His use of the word "intensive" suggests the need for "more oil" later in 1917.

Wrather (118, pp. 1028-1030) expressed a somewhat similar view. He felt that young geologists should work on the derrick floor and learn to "speak the language" of the drillers. As the trend seemed to be away from surface mapping as a guide to wildcat operations, these young men with broader technical educations should prepare themselves to supervise drilling and production operations requiring methods of conservation and intensive extraction of oil from known fields.

Schools for Petroleum Engineers

In 1914 several schools and colleges were giving courses in geology, fluid mechanics, and other subjects that concern petroleum technology, but there were at the most only two technical institutions in the country whose curricula led to a degree equivalent to that of petroleum engineer.

Indicating that instruction in petroleum engineering as such in the country's educational institutions was novel, or at least not commonplace, considerable space was given in a news item in a trade publication of May 1915, to reporting an address on oil-production methods by Prof. Roswell

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Johnson before the students of the University of Pittsburgh. Of interest to persons familiar with Kendall College, predecessor of the University of Tulsa, the press in December 1916 announced a short course of lectures to be given at the college dealing with petroleum geology, oil production, refining, and marketing. However, a complete petroleum-engineering department was not established there until 1928.

Lester Charles Uren, professor of petroleum engineering, University of California, has graciously supplied some historical facts to augment first-hand knowledge regarding the inception of petroleum-engineering courses in United States universities. There seems no doubt that Professor Johnson gave the first courses leading to the establishment in 1912 of the school of petroleum engineering of the University of Pittsburgh. It appears, however, that these first courses by Johnson emphasized petroleum geology and factors pertaining essentially to accurate appraisal of oil properties. The development of a full curriculum of petroleum technology seems to have come later, corroborated by the special mention of his lectures on production methods in the press of 1915, mentioned in the preceding paragraph.

In 1913-14 E. B. Durham gave a course in petroleum technology at the University of California, but his resignation terminated the initial attempt. When Andrew C. Lawson became Dean of the College of Mining in 1914 he conceived the idea of and took steps to put into effect a 4-year curriculum in petroleum engineering. Uren gave the first courses in 1915. However, the World War took many prospective petroleum engineers into service, and although the organization in the College of Mining was begun in 1915, it was not until 1919 that the full 4-year course "got under way."

Concurrently with Uren's first efforts, V. R. Garfias gave the first designated "petroleum-technology" course at Stanford University. This series of lectures (with copious reference and notebook work) was attended as extra curriculum by over 100 third- and fourth-year students in the several engineering departments. Many future petroleum engineers gained their first insight into natural reservoir behavior as controlled by geologic conditions from this elective, which proved to be no sinecure for anyone looking for easy scholastic credits. Garfias went to other less academic petroleum activity, and the petroleum-engineering department at Stanford did not materialize as such until 1919, under Frederick G. Tickell.

West Virginia University also rates a pioneer's place, as it offered a course in oil and gas engineering in 1916. Missouri (1920), Colorado School of Mines (1921), Oklahoma (1924), Texas (1928), and others were to follow as the need increased, owing to growing realization by the industry that the finding, producing, and transporting of petroleum and natural gas and the manufacture of products from them could no longer be done solely by those schooled in "rule-of-thumb" methods. The present courses at about 20 American universities and colleges giving degrees in petroleum engineering are outlined, together with other pertinent information in a recent trade publication (147).

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As part of the story of petroleum-engineering education it should be recorded that the Bartlesville (Okla.) division of the Doherty Training School for junior engineers (termed "J.E.'s") was initiated in the summer of 1916. The work included in this industrial training course has been outlined in detail by Briggs(28). Today, young graduate engineers starting to work for many oil companies receive special training from their employers before being given a definite assignment.

Consultants and Technical Books

A few consulting geologists and engineers were rendering service to clients in 1914, as several professional cards in the trade press and footnote title designations of some of the writers of technical papers indicated. For example, such cards as Associated Geological Engineers, "specialists in oil and gas problems," have been noted.

The petroleum Technologists' Pocketbook of Redwood and Eastlake (156) was published in London in 1915. A. Beeby Thompson (180), author of the volume Oil Field Development and Petroleum Mining, which was read widely by engineers and geologists in this country in later years, visited the United States in October 1916 after drilling water wells to supply the British forces in the Dardanelles campaign, to get first-hand information on drilling practices in Oklahoma and California fields. Another book that was beginning to receive attention was Practical Oil Geology by Dorsey Hager (76). A press announcement in 1915 emphasized that the book was written in language a layman could understand and was free from technical phrases usually contained in articles on oil geology. However, a book review (150) questioned whether all of the praiseworthy objectives of the author had been fulfilled completely, particularly in supplying a means of convincing "a skeptical oil man" that the geologist is of great value to him.

Bacon and Hamer (16) published their first edition of The American Petroleum Industry in 1916. Volume 1 was prepared with the assistance of F. G. Clapp, Roswell H. Johnson, J. P. Cappeau, and L. G. Huntley "to make the work a faithful record of present knowledge of the American petroleum industry." Clapp wrote the chapter on petroleum geology; Johnson was the author of chapters on valuation and efficient production; Cappeau dealt with appraisal work; and Huntley, elaborating on Bureau of Mines Technical Paper 51 (91) published in 1913, discussed the decline of oil wells in a chapter of 25 printed pages.

The complete volume (companion to volume 2 on refining) was generously footnoted, making it "suitable not only as a general reference work for those engaged in the industry but also as a text-book for students of petroleum engineering" (16, p. vii). Some statements made in later writings in the petroleum literature suggest that this work was not read as widely as might have been profitable for operators and students alike.

Another book coming from the press at that time was Principles of Oil and Gas Production, by Johnson and Huntley (96). This work was reviewed (63) as "probably the most comprehensive treatise on the geology and methods

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of producting petroleum and natural gas, which, up to the time of its publication, had appeared in this country * * *;" yet the reviewer was disappointed because, in his opinion, many subjects were inadequately treated.

Sears (166, p. 45), apeaking before the Natural Gas Association of America in 1925, recalled that the first printed data pertaining to natural gas were pamphlets supplied by a meter company as a part of its commercial catalogs. The first edition of Westcott's Handbook of Natural Gas was published in 1913 (138).

Petroleum and Natural-Gas Technical Societies

Open forums for the discussion of engineering subjects applicable to the petroleum industry were noticeably lacking in 1914, with one exception, to be noted later. It is true that the Natural Gas Association of America (later to become the Natural Gas Department and more recently the Natural Gas Section of the American Gas Association) was created much earlier. This organization resulted from a three-cornered conversation by representatives of natural gas companies, who recognized the advantages of gathering in one place for conference and discussion the managers and superintendents of manufactured-gas plants supplying towns and cities in eastern Kansas and western Missouri whose distribution systems were about to be changed over to natural-gas service.

Although an organization meeting was attended by 13 interested men on February 20, 1906, Sears (166), in his address Twenty Years Ago, stated that the first regular meeting was held on June 12 and 13, 1906, in Kansas City, Mo. and was attended by 63 persons. The first paper presented before the group was The Gas Engine as Compared with Other Sources of Power. This title probably suggests an important problem then confronting the organizers. In this connection, Natural Gas, former official publication of the association was published first in October 1920 (89), and formal joint technical studies by the association and the Federal Bureau of Mines did not materialize until May 1922 (66).

Early correspondence of the Bureau of Mines shows that on July 15, 1912, Joseph A. Holmes, first Director, pointed out to a large number of scientific and technical men the need for better general understanding of specifications pertaining to petroleum products. This action led to a series of conferences, at the invitation of Dr. Holmes, at Pittsburgh, Pa., about a year later in an attempt to coordinate and organize "inquiries of national scope through which knowledge in the possession of different investigators could be made available for the general good."

In addition to considering specifications, the proposed organization of what was termed "The American Petroleum Society" was seriously discussed. The organization did not materialize, but the conferences and meetings in contemplation of such a society resulted in better realization that "the industry is groping in the dark and that little accurate or general information is available." (68, pp. 3-4)

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The previously noted exception, as an organized open forum for petroleum discussions, is the American Institute of Mining Engineers (one of the four "Founder Societies" that later changed its name to American Institute of Mining and Metallurgical Engineers). In the 1914 edition of its Transactions (vol. 48), several petroleum papers were interspersed with those on mining of coal and the "hard-rock" minerals. Much of the material used in following sections of this paper has been gleaned from the annual volumes of "A.I.M.E." Transactions.

It should be noted here that Captain Lucas (in whose memory the Anthony F. Lucas gold medal has been established by the institute "for distinguished achievement in improving the technique and practice of finding and producing petroleum") became the first chairman of its Petroleum and Gas Committee in 1913 and again in 1914, 1917, and 1918 held the chairmanship of that group, which subsequently became the Petroleum Division of the American Institute of Mining and Metallurgical Engineers (5). He took a leading part in most of the early discussions and contributed several technical papers, to which later reference is made, based upon his observations regarding the occurrence of salt domes in the Gulf Coast region and the technique of drilling wells into them by modifying the "hydraulic rotary system" which led to his Spindletop discovery in 1901.

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Powers not only listed the geologists who attended the earlier meetings but gave the titles of the papers presented and the gist of the discussion of major subjects coming before the group during the period.5/

The American Petroleum Institute did not come into being officially until March 14, 1919, when A. C. Bedford, Chairman of the National Petroleum War Service Committee, received the decoration of the Chevalier of the Legion of Honor from the French Government (145). Petroleum Facts and Figures (first edition 1928, p. v.) states that the institute was formed as "an outgrowth of the activities of the National Petroleum War Service Committee, which service revealed the advisability and necessity of a permanent organization of such character," and reference was given to the four objects of the Institute as expressed in its charter, namely:

(a) To afford a means of cooperation with the Government in all matters of national concern; and

(b) To foster foreign and domestic trade in American petroleum; and

(c) To promote in general the interests of the petroleum industry in all its branches; and

(d) To promote the mutual improvements of its members and the study of the arts and sciences connected with the petroleum industry.

5/ After the manuscript for this report was written, J. Elmer Thomas (179) presented a paper before the 25th annual convention of the American Association of Petroleum Geologists in which he traces the growth of petroleum geology. His paper is a fitting sequel to that of Powers. Many details of the initiation of the group activities of petroleum geologists in the Southwest, which consummated in the organization of "A.A.P.G.", are recounted by Thomas as a background for his discussion of subsequent developments in the science of finding petroleum accumulations. Several of these developments are sketched briefly in the following sections of this report based upon the reviewed published literature of the period. The reader will find valuable augmenting material in the detailed treatment of Thomas given from his first-hand knowledge of this growth. (See also Oil Weekly, A.A.P.G. number, April 8, 1940.)

Thomas points out the difficulties that attend ascribing specific dates to the introduction of new principles or methods in the progress of petroleum geology - a condition referred to more generally in the beginning of this report. He also mentions the uncertainties of giving credit to the proper persons for discoveries because a practical idea may have been conceived 10, 20, or even 30 years earlier as a result of the work of searchers after facts, "perhaps in far-distant areas, whose pioneering work was not reported. Or, something may have been contributed by one man here, another by a second man there, while still a third, with or without knowledge of the others, produces a full-fledged theory, or method, or technique, which developes into a commercially important discovery. Such researches into history are quite fascinating as a study, although rather fruitless merely to ascribe credit."

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Early Work of Bureau of Mines

Almost from its organization in 1910 the Federal Bureau of Mines began its petroleum work; and its first Director, Joseph A. Holmes, and his associates were vitally concerned with methods for reducing wastes in drilling, development, storage, transportation, and refining. Wastes attending development and closely related activities alone were estimated to have cost the industry at least 50 million dollars in 1914. However, the Bureau's Petroleum and Natural Gas Division was not recognized officially as a unit, with W. A. Williams as chief petroleum technologist, until July 1, 1914.

The oil-trade press of 1914-19 made frequent reference to Bureau of Mines technologists participating actively in various discussions and field work relating to the conservation of petroleum and natural gas. This is not surprising in view of the fact that a motivating thought within the Bureau from the time the Petroleum and Natural Gas Division was constituted has been the development and carrying out of a coordinated system of research projects to collect, analyze, and apply the best available information regarding physical phenomena and other conditions controlling the behavior of oil and gas so that the ends of true conservation might be furthered.

The writer (68) has reviewed the early work of the Bureau on oil and gas subjects. The following excerpted paragraphs give as concisely as possible a thumb-nail sketch of important activities pertaining to petroleum of the Federal Bureau of Mines before, during, and immediately following the war.

> In those early formative years of the Petroleum Division of the Bureau of Mines the whole broad field of engineering and scientific research confronted the small group of technologists who first constituted this division. The insight with which an urgent need was sensed for broad and fundamental studies pertaining to petroleum and allied substances is reflected in the titles and subject matter of many of the earlier publications of the Bureau of Mines, many of which remain today standard references on the subject of petroleum technology (34).
>
> During the first years of the Petroleum Division of the Bureau of Mines there were few petroleum technologists in the employ of the oil companies, and, in addition to their basic studies, engineers of the Bureau were called upon to render all manner of service to the companies, frequently taking direct charge of the work, with the consent of the operators, in an effort to bring about corrective measures or improved methods. For example, the Bureau was the pioneer in advocating uniform casing programs and the cementing of wells, and by work on the derrick floor, the use of peg models, cross sections, and other devices operators were gradually convinced of the harmful effects of drilling into oil-producing formations without adequate safeguards against water encroachment.

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It was during this period when "in the consensus of opinion of well-informed authorities" demand for petroleum likely would exceed the productive capacity of the then discovered reserves, that the Bureau of Mines gave to the industry the basic and studied report of Lewis (106), which laid the groundwork for later research and extensive practical application of methods for recovering greater amounts of petroleum from the underground reservoirs.

During the late part of 1917 and throughout 1918 the activities of the Bureau of Mines on petroleum and natural gas were devoted largely to problems of the war. The personnel of the Petroleum Division, because of their training and knowledge of oil and gas matters, were in a position to give immediate service to the newly created United States Fuel Administration and to the armed forces of the country. Throughout the war period, in addition to the performance of a variety of confidential technical work, a determined effort was made to emphasize the prevention of waste of oil and gas, and their more efficient utilization (32).

At the end of the war "the Bureau was confronted with the need of enabling the mineral industries of the country to meet most effectively the inevitable difficulties that would confront them during the transition from the strain of war to the resumption of the normal activities of peace. Investigations in progress were stopped or given a new direction; plans for the future were changed; new investigations were proposed; work was concentrated on those investigations that promised to be most beneficial to the mineral industries during the period of transition and readjustment." (31)

As examples of peace-time activities, immediately following the war the Petroleum Division of the Bureau evolved a new method for estimating the future and ultimate production of oil properties (22, 51) under the then existing practices of so-called "normal decline", and a comprehensive study of underground conditions in oil fields resulted in a publication (2) on that subject, which is a continuing standard reference for all production engineers.

An oil-trade publication of 1916, reporting an annual appropriation of $70,000 for the Bureau of Mines to make inquiries and investigations concerning mining, preparation, treatment, and utilization of petroleum and natural gas with a view to improving economic development and conserving resources through the prevention of waste, made the statement, "It is evident that petroleum matters are receiving more serious attention in Washington now than ever before." However, not all the law makers in Washington agreed regarding the benefits to be derived from technical studies supported by Federal funds, because about this same time a member of the Congressional delegation from Massachusetts expressed his view that work of the Bureau of Mines on petroleum was an extravagance, declaring that the Federal agency was merely "disseminating information gathered by others." The Congressman probably was

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unaware of types of work to which reference has been given or that of Beal (21) in the Cushing (Okla.) field, then in progress.

Beal used underground structure maps extensively in an effort to determine the convergence in the thickness between the Layton and Bartlesville sands. He also studied conditions of oil, gas, and water in the various formations and the direction of migration of oil and gas. His studies showed certain peculiarities in the distribution of oil and gas, and he brought to the attention of the industry the inclination of underground water surfaces. Even today the use of the term "water level" is not well understood by some operators. On this subject Beal said in part:

> This "water surface" must not be confused with the surface of the ground water, which in an undulatory region is not level, and which is defined as a surface below which the rocks are saturated with water.

By way of illustration, Beal determined that the western dip of the "water surface" in one part of the Cushing field was about 90 feet in 1 mile.

In concluding his paper, which showed definitely that underground conditions affect reservoir behavior (although he did not use that term), Beal said:

> Undoubtedly our knowledge of the accumulation of oil and gas and the changing conditions under which they exist during development and during the productive life of a field, is slight, and much work of this sort must be done before sufficient facts are available for the formulation of any tenable theories to account for many of the present unexplainable phenomena encountered in oil fields.

He urged the necessity of work in other fields similar to that done in Cushing, and as rapidly as the facts are learned, "garnished by as few theories as possible," he thought they should be placed before the public to stimulate interest and to give others the benefit of the studies.

Although Beal's report on the Cushing field carried a title that might suggest the report to be purely geological in its treatment, it contains so much engineering material, based upon subsurface geology, that there is no doubt that his work was the forerunner of a series of engineering field reports written by Bureau engineers in ensuing years and now numbering nearly 50. The first of these to carry a designating title was written by Swigart (180) in 1919.

Many citations in addition to those given will be found in following sections of this paper to show other scientific and engineering work in progress by the Bureau of Mines from 1914 to 1919.

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Early Work of California State Mining Bureau

The first annual report of the State oil and gas supervisor of California (134) was submitted to Gov. Hiram W. Johnson, by Fletcher Hamilton, State Mineralogist, in November 1916. This report, by R. P. McLaughlin, the first State oil and gas supervisor, andhis deputy supervisors, covered the time from August 9, 1915, when the law establishing the Department of Petroleum and Gas of the California State Mining Bureau (now the Department of Natural Resources, Division of Oil and Gas) became effective (39), to June 30, 1916, the end of its first fiscal year. Specific reference is made later in this paper to particular sections of the first three annual reports of the State oil and gas supervisor of California, as they not only constitute a historical record of outstanding accomplishment in meeting technical problems in the oil fields of California during most of the period covered by this digest but also give a basic technical foundation for much of the engineering work on water problems in oil fields that followed.6/

These pioneers in the art of preventing injurious migration of water into oil and gas-bearing horizons were not psychic in knowing what the ultimate developments of their findings and pronouncements would be. Actually they were practical men with technical training who recorded with engineering exactness their appraisals of underground conditions and findings of fact that led eventually to better understanding of well-devised methods for protecting the thick oil-bearing sands of California from damage and resulting waste brought about by uncontrolled migration and infiltration of water and by other underground conditions.

Indicating an appreciation for judicious balance between oil-field practice and scientific fundamentals, the State mineralogist, in his letter transmitting the first annual report of the State oil and gas supervisor to the Governor of California, stated:

> It is of special importance to note that the details of administering the law (39) have been entirely in the hands of practical men who have had, in addition to the experience gained in the oil fields, technical training in various universities.

The names of some of the first deputy supervisors assisting McLaughlin have become well known in technical and executive circles of the petroleum industry during ensuring years. The first deputy supervisors were M. J. Kirwin

6/ Shortly after the California law became effective, McLaughlin (133) read a paper in San Francisco in which he drew on experiences of the California State Mining Bureau before passage of the Act of 1915. He pointed out that the greatest damage to oil deposits in California had resulted from water finding its way into oil-bearing sands and felt that an important function of the Petroleum and Gas Department under the new law was to gather all the facts and present conclusions much as a consulting engineer would for a client. However, he recognized the public interest his department was trying to serve in the conservation of oil, because in fields of divided ownership some solution to the water problem was necessary to assure that each of the several owners would obtain his share of the original oil that underlay his land - an early recognition of the theory of ownership of oil in place.

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(now chief petroleum engineer, Indian Territory Illuminating Oil Co.); Chester Naramore (the second chief petroleum technologist, Bureau of Mines, and now assistant secretary for the Petroleum Division, American Institute of Mining and Metallurgical Engineers), who was succeeded by R. N. Ferguson on October 1, 1916; R. E. Collom (now vice president, Continental Oil Co. of California); and Robert B. Moran (now consulting geologist and engineer, Los Angeles, Calif.). Later R. D. Bush (now State oil and gas supervisor of California), and H. W. Bell (now chief engineer, Rodessa Operators Committee) were among those who became members of that organization.

The California law had been developed on the basis of fact through careful studies by progressive oil operators of the time and technicians who were conversant with the more important principles of fluid mechanics. Before the California act of 1915, Fresno County, with M. J. Kirwan as oil-well commissioner, had been concerned with water problems in the Coalinga field; there had also been a water commission in Kern County.

This earlier work in California had its effect in other parts of the country. For example, Hager (75) wrote a short article in May 1915 illustrated by a figure showing diagrammatically "how waterflooding (natural) may and does take place in fields other than Cushing" (Okla.). Hager thought that conditions in Cushing were not essentially different from those of other fields and suggested an impartial water commission organized by the operators to protect the oil horizons against avoidable water intrusion. He called the attention of Oklahoma producers to the work being done by water commissions in the Coalinga and Midway-Sunset fields of California.

The general statement and review of the departmental work for the first year (1915-16) by the State oil and gas supervisor of California (134, pp. 5-34) reveals that he recognized a condition reiterated time and again in the technical press but until recently appreciated by only a few persons. McLaughlin said: "The general public is also vitally interested in preventing waste of the natural supply of petroleum." The initial work of his department in that direction was guided by a policy of administration that was designated as "uniformly lenient." Some individuals criticized this method of bringing about corrective measures, but the men charged with the conduct of the work for the State knew that the success of the new law depended on thorough and sympathetic understanding of the details of its working by operators and their employees.

He pointed out that "No definite rule or set of rules could be framed to cover all cases. Like all other engineering problems this (water in oil wells) is a subject demanding a tedious collection and combination of all pertinent facts." He went on to say that solution of the problems of his department required engineering skill.

Reading between the lines, it seems likely that the view just expressed was not unanimous in the industry, because McLaughlin was constrained to remark that his statement regarding the need for an engineering approach to the problem was neither "theoretical nor visionary." To substantiate his view further he gave the fact that "three of the largest companies in California are employing such a system." However, McLaughlin continued to observe:

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> There is probably no large business so inefficiently conducted as is that involved in the production of oil in California.

The original printing of that sentence is in italics.

Another "admission" or revelation of conditions of the time is found in his half apology that the report of one of his deputies might be judged too technical for most oil men, but he explained that the deputy "resides in the same community as theoperators and constantly discusses with them the points which are covered by the written report." Moreover, he optimistically hoped that in future enough companies would employ technically trained men to warrant such reports.

The second annual report of the State oil and gas supervisor of California for the fiscal year 1916-17 (135) was submitted to Gov. William D. Stephens on February 18, 1918. McLaughlin (135, p. 8) specifically recognized the extreme importance of saving oil because of the entrance of the United States into the war. He felt that public welfare would be served "for theutmost economy of labor and materials, together with the maximum production" by showing the extent to which latest and most approved methods were being used by the operators. Accordingly, he reported publicly the status of companies in the State with regard to their use of "thoroughly organized and competent technical departments for the purpose of studying underground conditions and directing development work." With one important exception, nine companies listed as each producing more than 1 million barrels of oil annually had well-organized technical departments or had indicated their assent to suggestions from the Department of Petroleum and Gas that henceforth they would utilize technical and scientific methods. Eleven companies each with less than 1 million barrels of oil production annually, are listed in the group where some scientific direction was given to the work. Nevertheless McLaughlin observed that too few companies "realize the importance of continuing to properly use the services of a geologist or engineer after the land has been selected and development commenced." He thought it a mistake to center attention on expensive pumping equipment to lift water with the oil and at the same time to ignoreunderground conditions that, if known, frequently would obviate the need for costly surface plants.

Exhaustion of the whole edition of the First Annual Report of the State Oil and Gas Supervisor of California in less than 1 year from its printing was an encouraging sign that technical information was being sought by the industry. To give the factual engineering information contained therein even wider distribution, the second annual report contained a reprint of those sections of the first that had general engineering application. These data were augmented by the experience gained during another year in carrying out the provisions of the Act of 1915. Other subjects also were treated on an engineering basis.

For example, specific instructions were given regarding the method of testing water shut-off in oil wells; operators were advised how to measure depths of wells and casing accurately - a technique that had been sadly neglected in the field, leading to inaccurate records and well failures; and general requirements for abandoning oil and gas wells were listed, with reasons for various schemes that would protect the strata.

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An innovation in petroleum engineering was a description (135, pp. 64-65) of how to construct and use peg models - adopted from a practice long used in the mining industry. These models helped greatly to visualize underground conditions that were difficult for inexperienced persons to grasp from cross sections and subsurface contour maps. Collom (135, p. 200), in studying field conditions and the possibilities of finding oil accumulation in the anticlinal structures of the Monterey shale in Santa Barbara and San Luis Obispo Counties, reported that peg models covering 2,250 acres (about 21 percent of the proved land in the district) had been constructed and that graphic logs were being drawn as rapidly as possible. This activity suggests the extent to which these graphic methods of portraying underground structures were being used in 1916-17 by progressive engineers. (Reference has been given in the section, Early Work of the Bureau of Mines, to its use of contour maps and peg models.)

In transmitting the Third Annual Report of the State Oil and Gas Supervisor (136), the State mineralogist was able to advise Governor Stephens on December 1, 1918, that "very gratifying results have followed 3 years of educational work, during which time both the department and the oil operators have advanced in knowledge of natural laws governing underground conditions." Because a few operators failed to "realize their responsibility in protecting the oil fields, in which the public is vitally interested" (as shown by the printed record of formal complaints), the need for certain changes in the law to make it more effective had become apparent; but in general the operators seemed willing to follow the engineering advice of the department.

The State oil and gas supervisor again referred to the conditions caused by the war that had made it clearly evident that the "national existence demands economy in almost all forms of material and energy." This objective, he remarked, depended on orderly and logical utilization of facts under scientific management and engineering methods. The number of companies conducting their operations on the basis of scientific method had doubled since the issuance of the second annual report. Although encouraging, there was much yet to be done because:

> The present shortage of oil as well as casing gives cause for serious reflection before the issuance of an order which either postpones theproduction of oil or requires an increase in the amount of casing to be used. On the other hand, the protection of the oil-bearing deposits is prime necessity, particularly in the present stage of national necessity (136, p. 419).

Physical Landmarks

A few physical landmarks will help the reader to identify the period of this review. The Cushing field, noteworthy for its effect upon the American petroleum industry and notorious because of the enormous waste of oil and gas during its early development, was in the throes of its "boom" period. Trade

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publications recorded the first birthday of that field in December 1914 1/ with the statement that 436 wells had been drilled during the year, causing a reduction in price of all petroleum oils in the United States, poor men to become millionaires, and rich men to lose their wealth, but over all the field had added little to the total income received by the oil producers of Oklahoma. Wastes in Cushing and other fields are discussed in later sections of this paper.

In California, Lakeview No. 2 well, which started to "gush" its first wild flow of heavy crude oil over the Maricopa Flats on March 15, 1910, was still being talked about as a phenomenon of prolific production from a deep zone (over 3,000 feet). Naval Petroleum Reserves No. 1 (Elk Hills) and No. 2 (Buena Vista Hills), both in the upper San Joaquin Valley in Kern County, had been withdrawn from public entry in 1912 (18, pp. 283 and 290). Elk Hills became a producing field in 1919.

Naval Petroleum Reserve No. 3 (Teapot Dome) in Natrona County, Wyo. was withdrawn in 1915 (18, p. 332).

Eldorado, Augusta, and Towanda in Kansas were flush fields of the period, becoming important in 1916 and 1917. Older Kansas operators remember hair-raising details of the famous "Trapshooter" well and others in Butler County that flowed "high, wide, and handsome."

Texas Panhandle

The great Panhandle oil and gas field of Texas, now comprising 36 designated producing areas, has left an indelible imprint not only on the oil industry of that State but also on the history of the whole country. The total quantity of oil that may be extracted eventually has been estimated as between 750 million and 1 billion barrels - a quantity almost beyond ordinary comprehension. Natural-gas transmission lines now extend from the Texas Panhandle more than 1,000 miles to various "city gates" (valves) such as those of Denver and Cheyenne, Chicago, Minneapolis, and St. Paul, and by interconnection even to Detroit - virtually revolutionizing the fuel economy of these and other urban and industrial centers.

1/ According to Beal (21), the Cushing field, which he designated the most productive light-oil field in the world, embraced "nearly 35 square miles of productive territory, in which have been drilled about 2,500 wells, ranging in depths from 1,200 to nearly 3,000 feet." Oil was discovered in March 1912 by C. B. Shaffer and others in a well drilled about 1 mile north of Drumright. This well was drilled to the Wheeler sand, and for more than a year and a half this and the Layton sand produced the entire oil output of the field. Development of the Bartlesville sand began in December 1913 with the completion of a well drilled by the Prairie Oil & Gas Co. At one time the daily production of the field was more than 300,000 barrels of oil, and when Beal reported in 1917 more than 200 million barrels of oil had been produced from all sands in the field.

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Little was known of this vast store of energy and wealth at the beginning (or even at the end) of 1914-19. To have the story from its beginning the pages must be turned back several years to show how the keen, scientific observation of one person may culminate in a new order. Not that the Texas fields of the Panhandle would have lain hidden indefinitely if C. N. Gould in 1903-05, while professor of geology at the University of Oklahoma, had received no commission from President Theodore Roosevelt to trace the water sources of the Canadian River drainage area for use of the Federal Geological Survey. Some one would have found the surface evidences eventually and explored them with the drill, but the fact remains that the Panhandle "discovery" was based upon the early reconnaissance of a geologist trained to read the history of the earth in rocks and their deformations.

Bartlett (19) has supplied the factual material upon which the following paragraph is based.

During his work in Potter and Hutchinson Counties, under the Presidential commission, Gould noted and mapped the gigantic structure running southeast-northwest through the Panhandle, now known as the Texas Panhandle oil and gas field. However, it was not until 1916 that Gould recalled and reexamined his notes on the Panhandle area while employed by M. C. Nobles of Amarillo. Nobles, learning of this structure from Gould, requested him, with some other geologists, to map the area more carefully; as a consequence, in October 1916 work was begun on the first well in the Texas Panhandle, about 30 miles north of Amarillo in Potter County. Bartlett states that the well was completed in December 1918 at a cost of $70,000. The depth was 2,605 feet and the initial production 10 million cubic feet of gas daily. Several other gas wells were drilled in the vicinity, and one of these had an initial open-flow volume of more than 100 million cubic feet daily. Oil was not discovered until a few years later. The first oil well was completed May 2, 1921, by the Gulf Oil Co. in Carson County, several miles east of the gas wells. The initial oil production was 175 barrels daily. Lack of pipe-line facilities and other conditions retarded intensive development, however, and it was not until 1925-26 that big wells flowing oil in the Borger area led to the ensuing "boom" and mushroom growth of Borger and other Plains towns of Texas.

OPINIONS ON THE GENESIS AND ACCUMULATION OF PETROLEUM (with Special Reference to Salt Domes)

As noted, in consequence of the representation of those associated with the petroleum industry at the February 1914 meeting of the American Institute of Mining Engineers, the resulting papers and discussions in its Transactions assumed an increasingly prominent place. There, writers of highly scientific discourses handled a fairly large share of the program, with those who discussed the more practical side of finding and developing petroleum deposits.

For example, Von Hofer (88) submitted his arguments, evidence, and rebuttals to contemporary writers in support of the organic hypothesis of petroleum origin, whereas Coste (48) continued to argue from a list of physical and geological observations that rock disturbances traceable to volcanic action were the most plausible explanation of the origin of petroleum. Other discussions on the genetic source of petroleum and its accumulation comprised a considerable proportion of the technical literature of the time (53, 59, 116).

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Even Captain Lucas, whose discovery of Spindletop in 1901 started activity alongthe Gulf Coastal plain where virtually every salt dome had become a prospective oil field, leaned to the view that the formation of these domes was traceable in some way to igneous origin. In discussing the paper by Von Hofer (83), Lucas referred to early drilling of a salt dome on Jefferson Island, La., and described his observations of many peculiar conditions that were difficult to explain. He stated that at a depth of 2,100 feet the drill was still in the salt and that the total thickness of explored salt was nearly 1,900 feet. Inasmuch as oil was not supposed to be present below rock salt or dolomite the well was abandoned; however, he was anxious to have a well drilled to a depth of possibly 6,000 feet into a salt dome but realized that more expert drillers and better tools were necessary.

He suggested using a diamond drill to obtain a sample of the underlying material, which at that time he believed must have come from a volcanic source. In 1917, Lucas (114) urged again further exploration of one or another of the domes along the Gulf coast to determine the "genetic relations of the oil, gas, sulphur, and salt." He recommended (as in 1914) drilling a well to 5,000 to 7,000 feet at a carefully selected point "to arrive at a conclusion more practical than the innumerable hypothetical suggestions now (October 1917) current." And in 1918 Lucas (115) presented still another formal paper before the institute in which he expressed his view "that all the salt-dome oil has had a common origin." He described oil and gas inclusions in salt crystals, taken from wells, and on the basis of a hypothetical sketch of the Belle Isle dome in which a deep-seated igneous plug was shown to have ruptured the Permian (?) and domed and fractured the Cretaceous (?) he stressed the desirability of drilling a deep well through the salt to the oil-bearing formations which he thought would be found beneath.

De Golyer (56) helped greatly to clarify hypothetical and analogical reasoning about the formation of salt domes by his studied review of the volcanic and other theories represented by various students of the subject.[g/] Acknowledging such favorable evidences as gypsum, free sulfur, hydrogen sulfide, and the relatively high temperatures of sulfurous waters, his study led him to conclude that the volcanic theory left much to be desired in explaining such important phenomena as "the formation of a tip of salt over 3,000 feet thick, as at Humble, on the end of an igneous plug during the course of or preparatory to an upward thrust which would result in considerable displacement of contiguous rocks" - sometimes 3,000 to 3,500 feet. He pointed to the theory of intrusion of salt by flowage and urged American geologists to give that subject more consideration in the future than it had received in the past. Dumble (56, pp. 470-477), in his discussion of De Golyer's paper, also discounted the volcanic theory and described the domes of the coastal plain as "structural features, consisting of bosses or stocks of salt, gypsum or anhydrite, or of combinations of these, intruding into and occurring in connection with broken and uplifted sedimentary beds of Cretaceous and Tertiary age."

g/ Powers (156, p. 155) recorded that one of the major subjects that attracted wide attention of the Southwestern petroleum geologists at their meeting in Norman, Okla., January 1916, was theorigin of salt domes - stimulated by the Harris theory of the linear force of growing crystals (83).

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This intriguing subject of the formation and characteristics of salt domes continued to attract attention for many years and led to a symposium, Geology of Salt Dome Oil Fields (3), published by the American Association of Petroleum Geologists in 1926, to be followed by a second symposium, Gulf Coast Oil Fields (4), published by the association in 1936.

EXPLORATION

The conclusion must not be drawn from the foregoing section that the chief concern of geologists and "practical" oil men was to establish an acceptable theory to explain the genesis of petroleum and the genetic reason for salt domes.

From the beginning of the industry, through 1900 and even later, prospecting was done largely by means of random drilling suggested by seepages and other surface evidences, although some credence was given to the anticlinal theory of Hunt, Andrews, and Hoeffer, rediscovered by I. C. White in June 1882 (41, p. 346, 190). Trend lines also were recognized by some prospectors and as stated, salt-dome drilling had been initiated with the discovery of Spindletop.

Surface Evidences and Surface Geology

Late in 1915 W. C. Moore, well-known producer, had distributed widely in the Gulf Coast area a booklet entitled "Indications of Oil in the Gulf Coast Country," prepared by a geologist. Without a single exception some or all of the following surface indications of oil were said to be present in the near vicinity of each discovery: Asphalt, gas, sour or sulfur dirt, paraffin dirt, sour or sulfur waters, and brine springs. One statement of the booklet might be remembered advantageously at present:

> It must be borne in mind that the drill and the drill only can prove the existence or nonexistence of a pool of oil at a point at which the well is drilled.

In 1918 Matteson (119) presented a paper dealing with prospecting along the Gulf coast. In addition to giving the history of important pools and his views on the origin and structural features of salt domes, he described surface evidences such as gas seeps (differentiating carefully between the behavior of bubbles caused by marsh gas and other gases) and other emanations, including "paraffin dirt."

The literature shows considerable discussion and diversified opinion regarding this peculiar substance, which eventually led to a paper by Brokaw (29), who described the curdy, rubbery "stuff" that "broke like green cheese" when moist but became a hard and horny mass of clods of high tensile strength when dry. Chemical analysis suggested to Brokaw that the material probably was not paraffin in the true sense but a form of peat or peaty soil. As an evidence of oil and gas, according to Brokaw, its occurrence rested "on the possibility that it may indicate gas-saturated soils* * * in the vicinity of gas seepages," but he thought it did not follow necessarily that paraffin dirt would be found at every gas seepage. In discussing this technical

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treatise, the president of an oil company operating in the Gulf Coast region was not convinced by the scientist's appraisal of the material and gave a relatively long list of places where paraffin dirt had been found and where wells had been drilled successfully on the sole basis of its occurrence at the surface. As Thomas (179) has pointed out, early studies of the phenomenon of paraffin dirt may have been the forerunner of the present developing technique of soil analyses as an aid to exploration.

At the beginning of the period (1914) drilling depths were relatively shallow, and surface structure, combined with other surface evidences that might be present and could be recognized easily, was the usual clue to the existence of conforming structures that might underlie the surface topography. Many test wells were drilled at the very top of surface "highs." De Golyer (57) says that the earliest mapping of surface structures was done with cyclometers, hand levels, and spirit levels, but by 1913 the plane table had come into general use.

Although some technologists were giving more and more attention to the correlation of well logs and were using underground contour maps to aid in interpreting structure (2, p. 67, 7, pp. 36-38, 10, p. 46, 14, pp. 108-110, 21, p. 18-19, 41, p. 346, 134, p. 209), surface geology continued to be the mainstay of most prospectors for several years, combined with courage to drill wildcats on surface indications. Some were inclined to apply scientific wildcatting to their exploratory operations. For example, Roy Johnson, then of Ardmore, Okla., expressed the view that wildcat drilling should be conducted in accordance with geological deductions. He said that it was unfair to blame the man who found an anticline or other structure if nature failed to place oil in it. Subsequent events in the petroleum industry suggest that Johnson's view preceded by at least one and possibly two decades common opinion in 1916.

Prompted by the international urge to produce more oil quickly, exploratory work was being pushed on many fronts. This condition is revealed by the number of wells completed annually. In 1915 approximately 14,000 wells were drilled, whereas in 1916 there were over 24,600 and in 1917, 23,400. In 1918 the number increased to nearly 25,700 wells.

Hager (77), in February 1917, tabulated 75 pools, largely in Oklahoma, with a few in Kansas, showing that all but four were well-defined structures. Of 45 of these pools discovered in 1913 and later, two-thirds were found as a result of geological work. However, he could give the geologists credit for only one terrace discovery. He concluded that the geologist had proved his case and the results of geological exploration had become so well-known that virtually all the larger oil companies of the Mid-Continent were depending more and more on this type of service.

In the discussion that followed, H. A. Wheeler gave further indication of the growth of geological service from 1913 to 1917 in his statement that a majority of successful operators in 1917 were making use thereof. Formerly they were ashamed to consult these "rock hounds." He ascertained that at least 200 geologists were employed by the larger oil companies, either as regular employees or as consultants, whereas 4 years before "there was one lone voice crying in the wilderness."

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From California, Kirwan (135, p. 156) reported that the Montebello field, proved as a producer of oil on February 24, 1917, with the completion of a well spudded on December 2, 1916, had been found solely because of "scientific geological study and not as the result of development along oil seepages."

A person need read only a few of the reports of the Federal Geological Survey prepared during 1914-19 and even earlier - for example, the writings of Arnold and his associates on the petroleum geology of California (7, 10, 14) and the first few volumes of the Bulletin of the American Association of Petroleum Geologists (156), augmented by the recent review of Thomas (179) - to appreciate advances being made in the science of oil exploration.

Subsurface Geology

Roswell Johnson (77, pp. 848-850), discussing Hager's table of oil-field discoveries thought it told only part of the story of exploratory work in the Mid-Continent because accumulations of oil in Oklahoma and Kansas seemed to be controlled not only by structure but also by lithology. Johnson defined lithology as a "change of porosity" and said specifically:

> The time has come when the producer needs to have his attention called to the importance of subsurface mapping.[9/] These maps that we can make of the structure of the surface are, of course, very valuable; but is not the producer of today depending on them too much? Is he spending enough time on the divergence, thickness, and nature of these sands?

He argued further that if anticlinal accumulation held for all pools in the area there would be a greater number of typical "textbook" structures with a gas cap surrounded by a ring of oil wells, and he noted the predominating absence of these rings in the Mid-Continent area. Johnson's early and incomplete pronouncement may have been a premonitory view of a better understanding of the stratigraphic accumulation of oil so clearly presented by Levorsen (105).

Well Logs and Cores (Limitations of Rotary Logs)

M. M. Thompson, in discussing Hager's paper (77, pp. 853-854), pointed out that where convergence or other stratigraphic conditions were more pronounced than surface folding, geology (based upon surface structure alone) had little value. He deplored the lack of reliable well records and stated that of 100 logs supplied by two large and established companies not one gave the elevation of the top of the hole, and that the classification of key beds was subject to many errors.

This reference to unsatisfactory drilling records was not a new subject before the American Institute of Mining Engineers. In discussing a paper presented in 1915 (133, pp. 237-238), A. F. L. Bell stressed the likelihood of passing up good oil sand with the rotary because of the difficulties of logging

9/ Arnold and associates had used the method in 1907-10 (7, 10, 14). On the use of subsurface maps as aids to petroleum engineering see Beal (21, pp. 18-19), Collom (134, p. 209), Ambrose, (2, p. 67); and Cattell, Fowler and Kraemer (41, p. 346).

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and cited one well in which only a few gas bubbles showed in the mud fluid. Later this horizon was tested, and a 10,000-barrel oil well resulted. In another well large quantities of oil were contained in the mud fluid, but only a 15-barrel well was brought in. Conditions such as these had caused some operators in California to employ "combination" methods. Rotary tools were used above a known oil-bearing sand, and the well was finished with cable tools. (See Woodworth (192) for a description of combination rigs.)

Collom (136, pp. 115-119) found this to be a continuing condition in 1918. Because 50 percent of the rotary jobs in the Sunset field at that time were failures he had reason to believe that the identification of various formations penetrated by the drill required study and improvement. Even with extreme care, 2 to 2-1/2 hours of continuous mud-fluid circulation was required (for a hole 2,500 feet deep) to get "returns" that could be identified satisfactorily. In the Coalinga field operators were questioning rotary programs then in use, and at least one operator in that field was planning to drill with rotary to a well-known "marker" bed and enter the oil horizon with a string of smaller-diameter cable tools - virtually the same "combination" method previously mentioned by Bell.

The increasingly unsatisfactory condition with regard to well logs evidenced itself in a paper by Matteson (117) before the American Institute of Mining Engineers in 1917, in which he called attention to the careless and unsystematic manner in which many drilling logs were recorded. The objection voiced by some operators that logs obtained through private investment constitute stock-in-trade was acknowledged by Matteson, but he thought the arguments in favor of systematizing well records outweighed other considerations.

Naramore, in discussion, stated that well logs in California had increased in accuracy after the State mining bureau had shown the need for better records, but with the increasing use of rotary-drilling methods in that State the logs again seemed to become less reliable. The time factor was important because formerly with standard tools 1 to 1-1/2 years was required to drill a deep well, whereas rotary contractors might drill a well in 30 to 35 days. Similar to Bell's earlier experience, Naramore cited one contractor's effort to "make hole." The night tour had drilled 200 feet through the oil sand and detected no oil, and it was not until a year later, during an attempt to salvage casing from the well, that the oil sand was discovered. At the time, in Naramore's opinion, there seemed little that could be done to correct the condition brought about by the inconsistencies in logging by different rotary drillers. Some coring had been tried, but there was criticism also of the geologists who examined the samples, because operators claimed that seldom did the geologists agree on interpretation of the core records.

Matteson's short supplemental paper (2-1/2 printed pages), given at the next following meeting of the institute (118), brought forth nearly 21 printed pages of discussion regarding well logs and related subjects. None of those participating in the discussion failed to recognize the "practical importance of well logs" - emphasized later by Bates (20) - and the difficulties of accurate logging in rotary drilling; but strong opinion was voiced that it was inequitable "to compel a company to divulge private information which has cost considerable sums of money to obtain."

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In his discussion, I. N. Knapp (118, pp. 1024-1025) stated that although an experienced rotary driller could tell instantly a change from hard to soft formation (or from soft to hard), little more could be known of the formation until some time after it was drilled because of the "lag" of the cuttings coming to the surface. He recounted that while he was operating in the Gulf coast a core barrel was purchased "similar to those that have been successfully used in coring coal and slate, but it proved a failure in unconsolidated material. From the experience thus gained, I designed a hollow bit and core barrel which proved a complete success in getting cores in soft material."

Knapp also told of a forerunner of the side-wall sampler observed by his son (Arthur Knapp) in Russia. The tool used by the Russians at that time resembled a casing splitter (ripper) (50, pp. 39-40). With suitable manipulations at the surface, a scraper was forced from the body of the tool, which gouged a sample from the wall of the hole. The sampler then was pulled up 1 or 2 feet and lowered again. This action pushed the scraper out of the way (presumably within the tool), and the assembly, with its wall sample, was brought to the surface.

Coring methods are not described in detail in this paper. Although these devices are mentioned occasionally in the reviewed literature, the impetus to intensive coring with ingenious tools followed the 1914-19 period, as shown by Cattell, Fowler, and Kraemer (41, pp. 347 and 349).

Diviners of Oil

During 1914-19 divining-rod artists were common on the Gulf coast as well as in California and other States.[10] These locators were described in the trade publications as embracing every form of "stick man." Some appeared with apparatus costing thousands of dollars; others were content to use the old "witching stick," dating to antiquity. Early in 1915 Mine, Quarry, and Derrick of Alberta, Canada, carried an item stating that "a geologist as a petroleum diagnostician is a product of recent years. Nevertheless, in a comparatively short time he has succeeded in coordinating a great bulk of facts, at the same time winnowing out a deal of chaff." The article continued to report that despite all this a company operating in Canada recently had shut down a well, the favorable position of which had been recommended by four geologists, and had started to drill at another site selected by a "chemical-ball" expert.

The Canadian operators were not alone in gullibility. As late as 1919, a California oil company of considerable importance, known to have "hard-headed" business men as officers, directed one of its surveying crews to "tie-in locations" made by two "doodlebug" operators. The survey required several weeks, and a well was begun in accordance with one of the recommendations of the "experts" on a steeply dipping spur of the Coast Range. After granite was found at less than 1,000 feet and the site abandoned the company lost interest in this type of prospecting.

10/ According to Powers (156, p. 155), at the meeting of Southwestern petroleum geologists at Norman, Okla., January 1916, a paper by J. Elmer Thomas entitled "Doodlebugs" and discussion of the general subject of licensing geologists called attention to the large number of "quacks" engaged in "locating" oil.

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Although technical men looked askance at persons professing to have some metaphysical power in divining the position (and even the condition) of underground structures, Charles N. Gould, former State geologist of Oklahoma, in November 1916, after a revealing discussion of divining mechanisms, stated in part:

> The day is coming when science, by means of a device which is being developed, will be able actually to locate bodies of oil. It sounds like a fairy tale to practical men when anything of this sort is told, but just mark my words, a real divining instrument is coming, and it will revolutionize oil-locating.

In the light of knowledge regarding present geophysical methods of determining favorable structure, Dr. Gould was then a prophet without honor in his own country. However, it was not until the early 1920's that geophysical methods of prospecting were used in the Gulf Coast region, although artificially excited elastic earth waves were applied to some extent in determining local geologic structures as early as 1913 (41, p. 347).

Cost of Exploration

In making this review no figures have been found to show the cost of finding oil before the early 1920's, when, according to De Golyer (57), it was 20 to 25 cents a barrel. Prospecting costs probably were higher from 1914 to 1919 because then more wells were drilled on the basis of "hunches" or pure wildcatting than later, although likely territory was more evident. In contrast with the relatively high cost of prospecting in 1920, De Golyer estimated that such costs in 1939, based upon good practice, were 10 to 12 cents a barrel.

DRILLING

Derricks and Derrick Safety

The year 1914 takes the reader back to the era when "forests of derricks" had almost literal meaning - especially in closely drilled fields. The predominating structural material was wood, and the carpenter-rig builder was a special type of artisan now almost vanished. The adz and derrick hatchet were his most important tools. The "running" of a wooden derrick was a breath-taking sight of coordinated man power. An efficient head rig builder felt chagrined if his crew could not run an 84-foot derrick in one 10- or 12-hour tour, and "expert crews" boasted that they had built two derricks - height not given - between daylight and dark.

Many derricks for cable-tool drilling were less than 84 feet high; one well-known manufacturer of derricks carried a full-page advertisement about this time showing heights of 59 to 80 feet, and another advertised derricks for standard cable tools 72 to 80 feet high "suitable in every way for drilling purposes." However, in 1916 Bacon and Hamer described the "California Imperial" rig for cable-tool drilling, "being 24 feet square at the base and from 106 to 136 feet in height" (16, p. 279). In rotary drilling, derricks were being erected with the crown block extending higher and higher above the derrick floor to accommodate longer stands of drill pipe.

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In March 1915 trade publications referred to an interesting exhibit at the Panama-Pacific Exposition in San Francisco sponsored by J. F. Lucey Co. - a complete rotary outfit in operation, using a steel derrick 106 feet high erected by the Carnegie Steel Co.

About this same time a steel company advertised that "lumber suitable for first-class walking beams is now scarce and consequently expensive" and suggested the use of steel walking beams in their stead.

In Illinois, portable drilling rigs ("machines") were used to drill to the 1,200-foot horizon, but derricks, usually of wood, were preferred for greater depths. A few turnbuckle derricks were seen at that time, but rarely was an all-steel derrick to be found in those fields. The cost of a wooden derrick erected in Illinois was about $700.

Woodworth (192) has given the most detailed account (found in the technical literature of the period) of derrick design and construction, but some of his historical references were not authenticated. Possibly he had read the accounts of a pseudo-historian who left a clouded record of the beginning of the petroleum industry, because Woodworth stated, incorrectly (192, p. 219), that the Drake well was "sunk by hand."

Nevertheless, he discussed the design of rig members and joints in accordance with sound structural engineering principles and gave accurate descriptions of drilling machines of the "Star," "Cyclone," and other portable types. He also described National and Parkersburg semiportable drilling machines. The latter had a mast 58 feet high and was capable of drilling to 2,000 feet or more. Woodworth also described several types of bolted, wooden derricks, pipe (tubular), and steel derricks. His discussion of stresses in various types of derrick joints is phrased in the technical terms of a structural engineer.

Woodworth described in considerable detail the 106-foot, heavy California-type combination drilling rig on exhibition at the Panama-Pacific Exposition. He stated that this rig represented the culmination (as of 1915) in this line of development, being the most complete assembly of drilling machinery ever constructed and installed. The rig was provided with two engines, one to drive the rotary draw-works and table and the other for the cable-tool assembly. The walking beam was mounted on revolving center irons and could be swung out of the way when the rotary equipment was in use. This innovation permitted rapid interchange of drilling tools. Woodworth described many of the rig irons in dimensional detail. The steel foundations set on concrete blocks represented the best practice at that time.

The total weight of the rig, exclusive of wood floor, platforms, and nailing strips, was 81,310 pounds. The derrick was designed to sustain an ordinary working load of 223,000 pounds, with a safety factor of 4. The walking beam was of steel, and Woodworth described the design and construction of structural walking beams, stating further that a large number of steel walking beams were being used but that some drillers objected to them on account of their stiffness, which made difficult exact determination of performance of the tools at the bottom of the well.

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In concluding his paper, Woodworth stated:

> While it is not at all likely that the steel drilling rig will replace the ordinary wooden structure to anything more than a limited extent, particularly in the drilling of wells for oil, a sufficient number have been put into use to justify conclusions as to their advantages based on actual experience.

He observed that a manufacturer should be well satisfied if he could equip 1,000 wells with steel derricks (out of approximately 23,000 wells drilled per year).

In discussing Woodworth's paper, I. N. Knapp stated that he had used a combination steel rig and had drilled three wells approximately 3,000 feet each with complete satisfaction. His experience was that, even if he had abandoned the steel rig at the completion of the third well, he would have saved a small amount of money compared with using wooden derricks and paying $24 per thousand for make-up lumber to replace that wasted in the two moves. Actually he sold the steel rig at the completion of the third well for 70 percent of its original cost.

David T. Day, also discussing Woodworth's paper, expressed his view that it was only a question of time until steel derricks would be used extensively. He thought the greatest hindrance in this direction was the prejudice of drillers who preferred to hear a wooden derrick "creak" before it "pulled in."

At this time, some attention also was being given to proper guying of derricks to prevent overturning by high wind loads during storms. In 1914 experience in Illinois was that 64- and 84-foot derricks occasionally were blown over. After such damage the replacement usually was a 40-foot pulling derrick (189, p. 554). A wealth of information on derrick failures developed from two windstorms in January 1916 that swept over the Midway-Sunset field in California, wrecking approximately 1,100 derricks. The conclusion of Tough (182) that virtually all of the failures were the result of faulty guying led to much improvement in this important construction detail.

Other improvements were beginning to appear. Many fires had been started by the old-fashioned "yellow dog" - a type of open light that burned kerosene with a smoking, sickly yellow flame. Where electricity was available operators were beginning to wire their derricks for illumination; however, this innovation did not completely nullify fire hazards on the derrick floor and under certain conditions may have tended to increase them. Electric-light globes easily broken through rough handling or inadvertent blowing of rocks and other material from the well bore, were reported to have been the source of ignition for gas that had accumulated near wellheads.

The Bureau of Mines, concerned with safety in the mineral industries and aware of the dangers of highly inflammable petroleum gases, studied this particular hazard from electric lights near oil and gas wells and published the results of its tests (42). Some may smile at the recommendations of that period, namely, that incandescent lamps for use in gaseous places should be

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8 candlepower, 220 volts, with carbon filaments; tungsten filaments, being hotter, seemed to ignite the surrounding gas more readily when the bulb was smashed or the glass tip broken. The Bureau recommended that bulbs without tips be used. It is something of a mental wrench to recall that electric light bulbs had tips at the bottom where the glass blower sealed the bulb after the filament was placed. The use of strong metallic guards, outer globes of heavy glass of gas-tight construction, and metal conduit with gas-tight switches, fuse boxes, and other appurtenances were included in the suggested specifications for a safe electric-lighting system for oil and gas wells.

Deep Wells

Through the years the general public, as well as the oil fraternity, has shown great interest in deep-well records. Although the fact is not recorded, Colonel Drake doubtless derived some additional satisfaction from the knowledge that not only had he drilled the first well for oil but that the tools actually had "bored" 69-1/2 feet beneath the surface of the ground. Salt-brine wells of that period had been drilled much deeper.

As of June 8, 1916, the deepest well in the world was reported as having been drilled with cable tools to 7,350 feet by the Peoples Natural Gas Co. near McDonald, Pa. Drilling was begun in 1911, and the all-told cost was $50,000. The next deepest well was at Derrick City, Pa., with a reported depth of 5,380 feet. On September 14, 1916, the Producers Oil Co. held the world record for the deepest rotary-drilled hole at a depth of 5,410 feet in the Humble pool, Texas. The drilling time was 45 days, and the fact that there was neither twist-off nor fishing job was reason for rejoicing.

Deep wells with temporary records are mileposts of accomplishment, showing what can be done, but they do not represent average conditions. In an appraisal of this kind the status of an industry is depicted more accurately by correctly specified averages than by superlative conditions of a given date. Often the superlative of today is not even the comparative of a short time hence. Although the well that now ranks as deepest (15,004 feet) has been a record holder since 1938, its position has been challenged several times, and few persons in the industry will be surprised when greater depth is attained.11/

Drilling in Illinois

Wheeler (189) has given a clear, concise picture of oil-field conditions in Illinois in his paper of 1914. He records that most wells were drilled by contract in the Illinois fields because few companies owned their own tools. Usually the hole was delivered complete on a footage basis (this was termed a "turnkey job").

Wells to the 1,000- to 1,200-foot level were started with 10- or 12-inch drive pipe and completed with a 6-5/8-inch "oil string" of casing inside an 8-1/4-inch intermediate casing. Deeper holes were begun with 16-inch drive pipe and frequently were completed with a 5-1/6-inch oil string, a greater number of intermediate strings of casing being required to shut off top water.

11/ On May 1, 1941, the Continental Oil Co. well (K.C.L. No. A-2), near Wasco, Calif., continued to hold this deep-well record.

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The gas pressure was not great, and usually the oil sand was entered without the aid of drilling water in the hole. This practice was followed to reduce the likelihood of "passing up the pay." Straight holes were difficult to maintain because of niggerheads (boulders) or iron concretions in some of the shales.

At first the wells were given heavy shots of nitroglycerin (100 to 200 quarts), but better results were obtained with 20 to 80 quarts. In Illinois, at least, the electric battery detonator had largely replaced the "jack squib." (See section on Well Shooting.)

The following data by Wheeler show typical costs and drilling time:

Wild-cat drilling: $2 per foot
Machine drilling in noncaving districts (to 1,000 - 1,200 feet): $0.70 to $0.80 per foot.
Derrick drilling to deeper sands: $1.30 to $1.50 per foot (depending on haul and fuel).
Cleaning out after shooting: $20 to $25 per day.
For 12-hour shift or tour drillers: $5.00; tool dressers: $4.00.
The 1,000- to 1,200-foot sand required 14 to 24 days' drilling time.
The 1,600- to 1,800-foot sand required 30 to 60 days' drilling time.

Drilling in California

Guiberson (74) presented a clear, concise description of methods of drilling wells in California in 1915. Evidently, many who were accustomed to drilling wells in Eastern fields were critical of California methods. For example, in one of the early technical discussions, A. F. L. Bell (133, p. 237) answering the direct question of a Louisiana operator regarding the use of large casing in California wells, said that his inquirer was "not the first and only Eastern man who has thought we were extravagant in our work." Bell then pointed out that many wells east of the Rocky Mountains were drilled and placed on the pump for a sum needed in California only to build and "rig up" the derrick preparatory to drilling a deep well - about $4,000.

The California operators experienced great difficulty with collapsed casing; Guiberson, answering other Eastern operators who questioned why under those conditions the derrick was not skidded to a new location and a new hole begun, pointed out that the cost of drilling a hole to 2,000 feet (where a collapsed joint could be expected) might easily be $20,000. Therefore, every effort to salvage such a costly hole had to be made before it was abandoned. The Eastern operators were not familiar with formations that dipped at angles of 40° to 60°, causing crooked holes. Flintlike boulders embedded in formations of soft sand were another obstacle in these steeply dipping strata. To prevent a crooked or "out-of-round" hole, cobblestones often were dropped in the well bore. It is recalled that the cobblestones were about the size of a driller's fist; some were larger. Even when cobblestones were used the driller had to watch each turn of the temper screw very carefully.

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An extra string of tools ordinarily stood ready for use in well-equipped cable-tool rigs in California; this was known as the underreamer string, and in place of the customary chisel-nosed percussion bit the bottom of this string was equipped with an underreamer for enlarging the size of the hole and making it circular in cross section. Guiberson states that by underreaming and continually moving the casing during drilling a string of 15-1/2-inch casing could be carried to 1,500 feet and a 12-1/2-inch string to 2,300 or 2,400 feet; strings even longer than those mentioned had been landed successfully. However, spears and other fishing tools (50), and jacks to loosen "frozen" casing were used frequently.

According to Guiberson, cementing (described in detail in a later section), had become fairly well recognized as a necessary adjunct to the successful drilling of wells in California despite some opposition experienced by the California State Mining Bureau after the Act of 1915 became effective (39,134). The more progressive operators cemented their wells with at least 5 tons of cement and allowed them to stand full of water for 15 days before they were drilled into the oil formations - a procedure in contrast with formation shutoffs, practiced in many fields in Eastern States. If a well could not be bailed dry it was necessary to find the leak and repair the damage by the most feasible means at hand. Sometimes a packer was run into the hole, making possible sealing of the leak with cement. Again the defective pipe had to be removed, if possible, and a new string of casing placed and cemented in the hole.

Information on costs of drilling in California is given in Guiberson's report as follows: An operator expected his well to cost at least $10 a foot, it might cost $20 a foot, and $30 a foot was not uncommon. The drilling of a well to the producing horizon required 12 to 15 months; one well in Kern County required over 2 years to drill and cost more than $165,000.12/ Guiberson concluded that old-style methods would not be applicable to drilling of wells in California, and that new tools, heavier rig irons, and stronger derricks were needed.

Antedating Guiberson's article by several months, Lombardi (112), then in charge of development work for the Kern Trading & Oil Co. (later called the Pacific Oil Co., and finally consolidated with the Standard Oil Co. of California), gave one of the best descriptions of methods of deep drilling as practiced in the Coalinga field that has been found in the course of this review. Although presented in February 1915, this engineering discussion was not printed in a trade publication until three months later.

The difficulties and methods of reaching production in the neighborhood of 4,000 feet were described. Because of sand conditions, which Eastern operators could not understand, it was desirable to carry large-diameter casing 2,000 or 3,000 feet without using great lengths of conductor pipe. The objective was to shut off, with 10-inch pipe, the top water, which might lie within 100 feet of the oil sand. If the pressure was found to be too great, 8-1/2-inch casing was used for the water string. As stated in an earlier section, the American Petroleum Institute was not formed until 1919, and its work of standardizing of oil-industry equipment was begun still later. Lack of standards for all types of field equipment, particularly tubular goods, caused great annoyance and led to many well failures. It was not uncommon in running

12/ Ball (17, p. 464) writing about the same time, referred to wells in California being drilled to depths of 4,000 feet. The cost usually exceeded $15,000 and frequently was $50,000.

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casing to find that the threads on a joint of pipe being "stabbed" would not match those in the collar of the preceding joint run in the hole, because pipe from two or more manufacturers using slightly different gages might be delivered to a well; the pipe checker had a heavy responsibility to assure uniform casing suitable for a particular job.

In California fields the limit for 10-inch casing used in the rotary method was approximately 3,200 feet, although Lombardi thought that this depth might be increased soon. However, the rotary method at first was received coldly in California because of difficulties of recognizing oil sands penetrated by the drill. Core drilling ahead of the rotary bit had not come into general use. (See section on Well Logs and Cores.)

Lombardi's paper gave particular attention to cable-tool operations and their modifications. He stressed the desirability of reaching a depth of 4,000 feet or more with a string of pipe not less than 8-1/4 inches in diameter and of having this string free and movable at that depth with a minimum length of conductor pipe in the upper part of the hole. He referred to an accomplishment of William Keck, a well-known, daring, drilling contractor of the period, who set a 15-1/2-inch string at 2,300 feet, followed by a 12-1/2-inch string at 3,003 feet. This was noteworthy because the unconsolidated sands would not stand up if the tools were more than 40 or 50 feet ahead of the pipe.

The circulator system, by means of which mud fluid was used with cable tools, also was described in detail by Lombardi. The circulation of mud fluid under pressure downward within the pipe to return to the surface outside of the pipe was somewhat similar to the rotary system. To obtain circulation of mud fluid during drilling with percussion tools a casinghead similar to an oil saver was used.

The pipe had to be kept moving while drilling was in progress, and this was accomplished by means of a spider (special pipe clamp), swinging in the derrick. The system required a 30-foot cellar so that lengths of casing could be added as required during drilling, and an extra 40-horsepower boiler and a 12- by 4- by 12-inch pump were needed. The pump (handling the mud fluid having a specific gravity of about 1.4) was placed on the derrick floor between the tug side of the bullwheel and the side of the derrick. With the circulator system, 3,336 feet of 10-inch casing was set in 122 days' drilling time.

Lombardi and his associates recognized the limitations of casing then used. Joints frequently collapsed or would not withstand maximum "pull." He suggested that a desirable string of casing, capable of being set at greater depths, should be heavy on the bottom (to withstand hydrostatic pressure); light on the top (to reduce the weight of the string); but the top part must have the greater tensile strength. He also suggested the desirability of using an upset-end casing for the upper part of the string. The upset should be outside of the pipe. He called attention to the advantages of fewer threads per inch, stating that 8-thread casing would stand more screwing and unscrewing and general "grief" than customary 10-thread casing.

By using a hydraulic elevator operating in a cellar having a lift of about 22 feet (in place of the overhead spider) and with other suggested improvement, Lombardi thought it reasonable to expect that 8-1/4, 10-, and

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10-5/8-inch water strings could be carried to 4,000 or more feet in the Coalinga field with only a few feet of conductor pipe near the surface.

Before this section on California drilling practice is concluded, it should be noted that both Guiberson and Lombardi described some of the more progressive practices in the State. Remnants of early drilling equipment in some fields and remembrances of those who saw the machinery, tools, and appurtenances when they were new suggest that many wells were not equipped as were the Coalinga-type and "California Imperial" rigs (16, pp. 278-280).

Drilling in Other States

Lucas and others have given fairly complete descriptions of drilling methods in the Mid-Continent and Gulf Coast areas in connection with their accounts of various problems of the period, and the foregoing specific resumes of Illinois and California methods show the trend toward improved equipment. Bacon and Hamor (16, pp. 272-344) devoted an entire chapter of their volume 1 to oil-well technology in 1916. Nevertheless, a few additional items from the trade press and other technical writings of those years will help to round out the picture for parts of the country that have not been discussed specifically.

In his paper on the use of mud fluids in 1915, Knapp (102) described drilling equipment in the Gulf coast, where many of the operations were near sea level. An 84-foot derrick with a 20-foot square base could be "floated" on a 30- by 30-foot planked area. The derrick was set on 3 feet of cribbed blocking, and 2,500 feet of 4-inch drill pipe could be stood in the derrick. Two 35-horsepower "oil-country boilers," one double 8-1/4- by 10-inch reversible engine, and two 10- by 6- by 12-inch duplex mud pumps were used. The rotary assembly was designated "15-inch," and Knapp listed the customary auxiliary equipment. In describing the "hydraulic rotary drilling method," Knapp referred to Fauvelle's invention, in France in 1833 (97).

At the same 1915 meeting, Hughes (90) referred to rotary drilling operations for water and oil as early as 1880 in the coastal plain of Texas, Louisiana, and Mississippi. An ordinary, flat, diamond-pointed bit was used. The invention of the Sharp and Hughes cone bit in 1908 made it possible to drill much harder formations with rotary equipment. Hughes described the crumbling and chipping effect of the cones on the rock. Concerning its operation, he said: "The proper adjustment of the weight upon the bit is the secret of good work with this drill." His paper included a table of drilling weights on the bit and the caution that in very hard rock speed and not weight should be increased.

Keen (133, pp. 235-236) described drilling and cementing methods in Louisiana with particular reference to shutting off salt water. He mentioned particularly the use of only one plug in the usual cementing process. Ordinarily 30 sacks of cement were mixed with 15 sacks of sand. The mixture was poured into the casing to be cemented directly on top of the mud fluid. The wood plug (with rubber washers on both ends) was placed in the casing above the cement-sand mixtures; the swivel was screwed to the top of the casing

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(by means of an adapter); after the string had been lifted off bottom about 8 inches, the pumps were started to force the cement-sand mixture and plug to bottom. Although the pumps had to stop when the plug reached the bottom they might be stopped inadvertently for other reasons; to assure a successful job, a steel measuring line was run into the casing after the pumps stopped to determine whether the wooden plug actually was on bottom. The cement was allowed to harden 10 days before the plug was drilled out.

Some may believe that the Rocky Mountain region is one of the last strongholds for cable tools. This actually is true, as a recent survey shows that cable tools still handle two-thirds of the drilling in Wyoming and almost all of that in Colorado and Montana (148). However, it should not be inferred that there was no rotary drilling in the Rocky Mountains until recently. In March 1915, because ordinary cable tools (weighing 4,000 pounds) could not penetrate a gas stratum under high pressure in the Buffalo Basin (Wyo.) field plans to convey a rotary-drilling outfit to the well were reported in the press. It is not recorded whether the equipment reached its destination.

Again, some have considered the welding of casing a relatively new departure in drilling and production practices, but in December 1915 the Peoples Natural Gas Co. welded and placed over 6,000 feet of 5-inch casing in its deep well near McDonald, Pa. The total weight of the string was 45 tons. Incidentally, the first reference found to automatically controlled cutting with a torch appeared in a news item from Parkersburg, West Va., in June 1916, describing a pantograph with an automatic, electrically driven feed that operated an oxygen natural-gas burner capable of cutting patterns and other shapes from solid steel billets. The application of automatic cutting and welding to curved shapes such as tubular goods and pressure vessels came some years later.

Blow-outs and Wild Wells

Nowadays wild wells frequently are thought to be solely a recent affliction confined to the Gulf Coast area. The hazards of blow-outs during drilling have long been recognized by workers on the derrick floor, and the early operators along Oil Creek, Pa., during 1860-70 drilled first and then devised ways of capping their wells, or allowed them to blow until the pressure subsided. Wells were reported out of control in California[13] and in other States during 1914-19, when wildcatting in unprospected territory with inadequate equipment increased the hazards appreciably compared to what they are today - even with much greater reservoir pressures at increasing depths.

Wild or crater wells long have been a problem to operators along the Gulf coast[14]. This condition was shown by Keen (98), who comprehensively described methods used to extinguish a burning crater well that got out of control May 11, 1908, and was estimated to have blown 40 million cubic feet

13/ A "blow-out" occurred in the Midway-Sunset field near Fellows, Calif., during 1915, in what now would be considered a very shallow field. In the course of drilling at 1,930 feet, an unsuspected pocket of gas was entered, and the complete string of drilling tools (bit, jars, sinker bar, and rope socket) was blown out of the well, landing 400 feet from the derrick.

14/ For information on recent "blow-out" problems in high-pressure fields, see Carpenter, Charles B., Some Causes of Blow Outs During Drilling and Means of Prevention, with Special Reference to the Gulf Coast Region: Bureau of Mines Inf. Circ. 6938, 1937, 27 pp.

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of gas into the air in 24 hours. When the well was brought under control 5 years later, it still was blowing an estimated 8 to 10 million cubic feet of gas daily. This well finally was subdued, through efforts of the Conservation Commission of the State of Louisiana, by contracting for the drilling of a relief well 125 feet from the crater well and 832 feet in depth. After mud fluid had been pumped into the porous gas sand for 7 days the eruptions diminished in number and violence, and on the tenth day after pumping was begun the eruptions ceased. Mudding was continued for three more days. It was estimated that the well probably wasted 27 billion cubic feet of gas in all, valued at that time at $675,000. The cost of bringing the well under control was about $6,000.

Blow-outs and well fires became so numerous about the middle of 1915 that Johnson and Huntley (95) suggested that fire-fighting stations and emergency railroad cars manned by experienced crews be kept ready to fight them. Today several service companies maintain crews for just such emergencies going quickly to the scene in high-speed automobile trucks equipped with many devices, including asbestos suits to be worn by the men.

After the Johnson and Huntley article was published, a correspondent called the attention of the editor of the Oil and Gas Journal to the inadequacy of their proposal. However, conditions then were different. Many of the fires occurred great distances from railroads, and the heavy equipment used at that time could not be transported readily to the scene of the fire (24). The correspondent maintained that prevention by educating the industry as to methods of coping with the well conditions leading to blow-outs and fires was a better approach than overstressing means of extinguishing fires already burning.

To support the opinion that many wild wells resulted from carelessness, the correspondent cited a burning well in the Cushing field where the casing crew left the job for the night after running 1,600 feet of 6-5/8-inch casing because of difficulties in screwing together joints of casing that had come from three different mills. The gas was permitted to blow uncontrolled, and during thenight became ignited from a torch on the opposite bank of the Cimarron River. An oil-field worker on an adjoining lease was unable to shut in the well because no means had been provided. A control device on the wellhead probably would have prevented the well from getting out of control, or it could have been shut in after the gas was ignited. The correspondent believed that the general features of engineering efficiency in the oil country were as well developed in 1915 as in any other industry, and the serious wastes then occurring resulted from improper methods used by relatively few offending individuals.

Control heads and similar equipment of various designs were on the market at that time[15/] but were not used as widely as conditions warranted. Heggem (84) substantiated that observation when he wrote that in September 1915 about 1,000 control casingheads were in use. Approximately 14,000 wells were drilled

15/ See discussion by Arnold and Garfias of blow-out preventer, Mortenson well capper, and special methods used by J. A. Pollard for controlling gas wells.

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in the United States in 1915; this was a "low" between years of higher drilling rates, with around 23,100 wells drilled in 1914 and 24,600 in 1916. However, Heggem considered this 7 percent (approximate) a goodly number, because the caption of that section of his paper reads, "The Control Casing Head Now Largely Used." It must be remembered that he was discussing control heads and not gate valves, because he wrote that a customary gate valve placed on the head of a well "did not safeguard either life or property and really caused a false feeling of safety." He referred to the expediency of shooting off such a gate valve with a cannon ball before a well thus equipped could be brought under control.

Most of the essential requirements of a control head as named by Heggem, are just as pertinent today as in 1915: A proper closing and controlling device that will permit drilling operations to be continuous without interference; immediate and tight closing; safety to workmen; simple construction; compact size; strength enough to control maximum pressures (he referred to maximum wellhead pressures of 1,800 pounds per square inch compared with pressures of 6,000 to 6,500 pounds per square inch recorded at wellheads today); proof against injury in handling; resistance to sand and fire. One item in Heggem's specification of requirements of an efficient control device that suggests the thought of unrestricted production at that time is: The head should "control the flow without back pressure."

In territory being prospected, the control head was installed on top of the first string of casing landed in a well and kept there throughout subsequent operations. The core of the valve was recessed so that it would close tightly around the drilling line. Later, other designs of heads made it possible to shut in wells with drill pipe or casing in the hole. When any subsequent string of pipe was set in a well the end of the pipe was below the head, or the head was fitted on the inner string with a suitable swage nipple. Closing in gas between two strings was accomplished by means of a packing ring "screwed into the larger casinghead and a gas-tight joint made on the outside of the inner casing." It must be remembered that factory-built "Christmas trees" were still in the future.

Heggem also described and showed a sketch of a control head used in conjunction with a "lubricator" of improved form for introducing mud fluid into a well to "kill gas." He emphasized the advantage to having all operations controlled from the derrick floor without extra help being required.

In 1913 Bowie (24, pp. 27-32) reported his findings, extending back several years, on methods used by Clayton, Lombardi, and others to extinguish oil-well fires.

Drilling Through Workable Coal Beds

A hazard associated with drilling but requiring different technique to handle was the ever-present likelihood of striking entries, rooms, or other mine workings in the coal measures of some Eastern States. Moreover, in unworked parts of a coal field property and persons could easily be injured if a borehole for oil or gas were improperly cased, mudded, or cemented - failing to give adequate protection to the strata comprising geologic structures in a given area.

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In 1915 a bill was introduced in the West Virginia Senate to control the drilling of wells through workable coal beds. This bill was opposed by some oil operators because it was said to increase difficulties and add to the cost of oil and gas operations.

This problem engaged the attention of the Bureau of Mines and led to one of its early bulletins (160). The suggested form of State law given in this publication remained a standard reference for years (86).

Drilling Charts

Collom (136, pp. 196-197, and fig. 8) probably was one of the first engineers to use a graphic chart to analyze progress being made in drilling wells. This type of chart, modified to meet local conditions, has been and is being used widely throughout the industry in comparing groups of wells drilled in the same vicinity. By using a stratigraphic instead of a sea-level datum and a composite log of the geologic section, Collom showed how it was possible to compare drilling and production data for several wells in the same vicinity.

METHODS OF SHUTTING OFF WATER IN WELLS

In the section, Early Work of California State Mining Bureau, the statement was made that the first three annual reports of the State oil and gas supervisor and his deputies contained much basic technical information on water problems in oil fields.

To acquaint the California petroleum industry with some of the engineering factors involved in this major threat to the oil resources of the State - uncontrolled water - the primary causes of its entrance into oil-bearing sands were set out carefully and simply in the first annual report (134). These were discussed under two headings: (1) Incomplete knowledge of geologic conditions surrounding wells and (2) faulty mechanical conditions in drilling or maintaining wells. To simplify the discussion, sketches were used, and arrows showed the possible travel of water from and to strata in and about various types of mechanical equipment in boreholes under different conditions of geologic arrangement of strata. Although wells are completed today with types of equipment that differ from those used in 1915, the fundamentals shown in the original 10 sketches are as valuable now as when they were drawn.

A hindrance to complete cooperation of the industry with the new State organization, particularly in fields then opened in the Los Angeles Basin, was the attitude of many operators, who at first would not accept the basic principle that it is unprofitable (and often unnecessary) to lift both oil and water. Moreover, they failed to appreciate the generally existing condition that much of the water accompanying the oil was present in the producing zones because of faulty conditions in a relatively few wells in any given area. The State oil and gas supervisor voiced the desirability of making migration tests, but "the present (Oct. 1, 1916) extremely high cost of all (aniline) dyes makes such work impossible on any extensive scale.[16/]

16/ In 1920, Ambrose (2, pp. 106-121) gave a comprehensive review of existing knowledge regarding use of detectors for tracing movement of underground waters.

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Kirwan (134, pp. 60-115), reporting on the Coalinga, Lost Hills, and Belridge fields, not only recorded their histories - information of great value in later producing operations - but contributed generously to the fund of petroleum-engineering knowledge, the dearth of which has been shown clearly in other sections of this digest. For example, he stressed the need of shutting off water at the proper depth as among the most import phases of field engineering. The horizontal and vertical variability in porosity and saturation of sands was recognized, and case histories of wells were cited to show where productive sands were passed through without their potentialities being known or neighboring properties flooded, because basic principles were not recognized by operators.

Kirwan gave a clear description (for that time) of the function of "edge" water, differentiating between this type of encroachment up dip to replace the oil in the sand and "top", "intermediate," and "bottom" water. He also called attention to the value and practicability of using chemical analysis in identifying different types of water in oil wells. (See section on Water Analyses.)

As regards production records (including fluid-level information) and well logs (see section on Well Logs and Cores), Kirwan observed that many operators considered them "merely as official red tape." The general disregard for the essential engineering data they can supply was evidenced by their scarcity and the common method of keeping those available (usually originals with no copies) in field offices easily destroyed by fire. His examples of the use of production records from which charts were drawn to help solve water problems agree with accepted engineering practice today.

In similar manner, Naramore (134, pp. 116-172) described the first year's work of the Department of Petroleum and Gas of the California State Mining Bureau in the Midway-Sunset, McKittrick, and Kern River fields. Much of his time was spent in making tests for water shut-offs and in collecting well records and other data. Space does not permit detailed recounting of his observations in each of the fields under his direct supervision. However, mention should be made of his account of the then "old" McKittrick field, which continued to make a steady daily production of approximately 9,000 barrels of oil despite the very serious water problems caused by neglect of engineering principles during initial development. Naramore recommended repair work that probably kept that field in pumping status for years.

Moran (134, pp. 173-191) discussed each of the fields in the Los Angeles Basin and in Ventura County under his supervision, first on the basis of the structural geology and then as to water conditions; as he pointed out, the position of a well with respect to geologic structure is important, and an edge well might make large quantities of water without menacing wells up dip from it. However, he cautioned a careful study of local conditions - with dyes, if available, or an easily recognizable element such as lithium - where the source of water was in question.

In the West Coyote field water problems were complicated by the presence of lenses of gas sand distributed both laterally and vertically in erratic patterns. Because water was present immediately above the producing measures,

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the field men thought it necessary to cement the 8-1/4-inch casing (the principal shut-off string) with cement lowered in torpedo cans. After the cement had been placed in the bottom of the hole the tools were lowered, and the material was "tamped" into place around the casing shoe. (See section on Mudding and Cementing Practices.)

Moran stressed the position of the working barrel in wells making water, pointing out that under certain conditions a working barrel could be placed to skim the oil. If it were placed lower, the pump might not be able to handle the fluid. Moreover, if a pump were working at capacity, water probably was present in surrounding wells.

Collom (134, pp. 192-211) discussed the causes of water infiltration in the Santa Maria district. In his study of underground conditions in that district, Collom found that "records brought to the surface by the drill" were his chief source of information. From them (by means of cross sections drawn on the basis of drill cuttings and "by an underground contour map - scale of 1 inch to 500 feet") he showed the existence of "at least two principal domes with corrugated or short anticlines plunging away from the apices in various directions." In addition to working out water conditions from his underground-structure maps he concluded that it was reasonable to expect that other domal structures would be found in the Monterey shale of the Santa Maria district.

The last chapter of the First Annual Report of the State Oil and Gas Supervisor of California, prepared by members of his staff with the assistance of others, was the nucleus of what might have been a petroleum engineer's handbook with particular reference to methods of shutting off water.[17/] Uniform water shut-offs for various sands were urged repeatedly throughout the First Annual Report because difficulties resulting from nonuniform shut-offs had required increasing attention from the deputies.

That chapter of the First Annual Report on methods for shutting off water included discussions of the prevailing methods of cementing wells. The formation shut-off was referred to as having only a few followers in California, as hydraulic cement then was generally used to exclude water from oil sands in California wells (11). The "dump-bailer" method (in experienced hands) had given "a large percentage of successful shut-offs, even in deep territory." The tubing method also was described but appeared to be yielding to cementing through the casing. Reference also was made to the "two-plug" method and the procedure of measuring "water pumped in behind the second plug as a check on its progress" to the bottom of the hole. The quantity of cement used in a well ranged from 5 to 30 tons, depending on conditions, and in some wells the space between the casing and the wall of hole occupied by cement extended 1,000 feet above the casing shoe - to retard corrosion and prevent collapse of casing.

17/ This chapter also contains a short discussion of derrick failures (see section on Derricks and Derrick Safety, this paper), and one on the extraction of gasoline from natural gas by absorption method, contributed by Ben E. Lindsly, then engineer with the Honolulu Consolidated Oil Co. (see section on Natural Gasoline Extraction, this paper).

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The tables showing collapsing strength and equivalent head of water for nominal sizes of casing and those giving capacity per linear foot of casing and tubing of different diameter and weight should have been of great value in coping with water problems during that period when reference handbooks containing such factual data virtually did not exist.

Some years later, Hager and McPherson (79) gave a brief resume of water problems in Mic-Continent fields, showing graphically as well as describing in text the sources of water troubles in oil wells and their remedies. As Hager (75) had done in 1915 (see Early Work of California State Mining Bureau) these writers again called attention to the cooperative method by which California operators settled their difficulties arising out of water troubles.

Shidel (169) discussed water problems in the Mid-Continent, in which he summarized results of cementing wells in the Augusta (Kans.) field in an effor to exclude bottom water. In discussion, Ambrose also referred to the cooperation between companies in the Coalinga district that had resulted in greater oil production even after certain wells were thought by some to have "nopeless gone to water." Some of his remarks included reference to core bits on the bottom of rotary drill pipe to identify small "shale breaks."

Mudding and Cementing Practices

The California State Mining Bureau was not the first or only agency concerned with solving water problems in oil fields. Arnold and Garfias (11) had discussed the cementing of wells in California in a Bureau of Mines technical paper published in 1913; Pollard and Heggem (155, 85) during 1913 and 1914 wrote two other Bureau of Mines technical papers on mud fluid, to be followed by the bulletin of Lewis and McMurray (108) in 1916. The State oil and gas supervisor of California in his first annual report (1915-16) was reticent in giving unqualified approval to the mud fluid method for shutting off water because it was comparatively new in California fields and had not been adequately demonstrated. However, he was willing to have operators experiment with mixtures of clay and water (in which the finely divided clay in suspension might range from 5 to 25 percent) in favorable wells where the definite effects could be studied. After pointing out that underground conditions in Oklahoma and Kansas were different from those found in California, he referred in some detail to "the very useful work of introducing it (the mud-fluid process) among operators" in Oklahoma by the Federal Bureau of Mines and the Corporation Commission of Oklahoma.

Two papers on mud fluid and cement in wells evoked considerable discussion at the February 1914 meeting of the American Institute of Mining Engineers The use of these two materials was closely related in the minds of those entering into this forum. This was a natural relation of subject treatment, particularly at a time when doubt - or at least caution - was voiced by several engineers and operators regarding the effectiveness of mud-laden fluid in bringing about certain curative conditions in wells. Moreover, there was much to be learned about the best use of cement in wells. Some doubted whether mud fluid could be handled so as to have no contaminating effect on the cement.

Oatman (142) discussed theuse of Portland cement in wells in some detail. There were several procedures for getting cement (either neat or a mixture of

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10 to 15 percent sand with the cement) to the bottom of the hole. When tubing was used, a wooden plug with a rubber disk on top frequently was inserted after the cement (averaging 3 to 6 tons). Various types of packers were used to keep the cement from traveling back into the casing.

In the bailer method Oatman thought the best practice was to bail out the cement inside the casing if the pipe had been well-spudded into the shale. This made it unnecessary to drill out a plug after the cement had set - an operation likely to fracture the cement collar. He also described briefly the Perkins "two-plug" method (referring to cast-iron packers inserted in the casing). The Perkins method was described in more detail by Tough (183)[18] after the plugs or packers were made of wood.

Oatman's discussion of cement and its uses shows that a considerable amount of engineering information was available to the petroleum industry from building-construction experience. He referred to the effect of gypsum that might be added to regulate the time of setting. He stated that "up to about 2 percent" setting is retarded, whereas more than that quantity accelerated the setting time. He cautioned that only small quantities of gypsum be used in cementing off alkali water. He also discussed the effect of temperature on time of set and recommended finely ground cements for use in oil wells. In discussion, an operator stated that the two-plug method had application only to a few wells "where conditions for cementing are ideal," but this was not the general view of engineers at that time.

It may be significant that at the San Francisco meeting of the Institute, September 1915, (133, pp. 234-235), W. A. Williams, in referring to progressive cementing at the bottom of wells to exclude edge water, said in part:

> The method of cementing was simple but effective, consisting of placing the necessary cement in the bottom of the well, forcing the cement back into the sand with a pressure equal to a column of water possibly 100 feet above the ground-water level.

This statement shows that Williams may have had an incomplete idea, which if developed, might not have differed greatly from some of the currently used methods of "squeeze cementing."

Knapp (101) presented the second paper at the 1914 meeting of the institute pertaining to cementing and mudding practices. In the discussion that followed, O. P. Hood, Federal Bureau of Mines, questioned particularly a statement by Knapp that "the wobble of the rotary drill stem must do the plastering; it cannot be done efficiently in any other way." Hood's remarks from the floor were a scientific contribution - perhaps not fully appreciated at

18/ Gilman, C. J., reporting on California Operations, Oil and Gas Jour., April 15, 1915, p. 22, gave an interesting account in Albert A. Perkins' own words of how the idea of cementing wells to prevent the shifting of sands occurred to him while drilling water wells for the Winchester Repeating Arms Co. at New Haven, Conn., in 1892. It appears that business with the two-plug method was not very brisk when Gilman interviewed Perkins in California.

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the time. He said:

> .... A fluid may flow from a formation into a borehole because of reduced pressure in the hole, but the direction of this flow can be reversed by creating a fluid pressure in the hole greater than that in the formation. The amount of radial flow will depend upon the pressure difference, the porosity of the formation, and the viscosity of the fluid ....

Knapp (102) again treated the subject a year later, using the coined term "mud-ladened water." Most of this paper dealt with methods and equipment used in his own drilling experience; however, some of his findings regarding the behavior of mud fluids contributed new ideas. He observed that mud fluid having a "head" of 57 pounds per 100 feet (as compared with clear water, which exerted a pressure of 43 pounds per square inch per 100 feet of depth), gave a good margin of safety in wells then being drilled in the Gulf Coast plain. Again, because he had observed that one mixture would settle rapidly, whereas another would stand for 6 months without settling, he concluded that the rate of settling did not depend solely on the differences in specific gravity. He stated that the material in suspension imparted a certain viscosity to the fluids. His technique did not take him to the laboratory because, in Knapp's opinion, the only sure way to find out the characteristics of a mud was to mix and try it, and he referred to tests that he had made on the derrick floor.

Knapp described a crude but what he claimed effective procedure as follows: Mud fluid was placed in a bucket to one-third its height; then half a bucket of clear water was added and the contents stirred thoroughly and allowed to stand undisturbed for half an hour. If less than 1 inch of clear sand settled to the bottom of the bucket, Knapp believed that circulation in the well of mud fluid having characteristics of the original sample was reasonably safe. He failed to explain what might take place in the well during the half hour of settling if circulation were maintained throughout the period and the mud fluid failed to show the proper characteristics, but he did refer to the use of a hand centrifuge for determining the percentage of sand in any mixture - which had more appeal than the "boiler house" method just described.

One practice is especially noteworthy - that of weighing the mud fluid. Knapp used a common market beam-scale and observed that sand may give weight but not impart the proper consistency to the circulating fluid. He voiced a belief, in his paper, that the testing of mud fluid by weighing was a novelty in the industry.

As mentioned, the State oil and gas supervisor of California in his first annual report (1915-16) expressed some doubts regarding the use of mud fluid in California wells as a general practice until the method had been tested further. His second annual report (1916-17) suggests that mudding practice was growing in California as a means of preventing migration and infiltration of water into oil-bearing sands. McGregor (132) described in some detail methods by which wells were plugged with clay: (1) By mixing the clay in the well and (2) by mixing the fluid at the surface before placing it in the well.

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In one well described by McGregor, about 850 cubic yards of clay, 4-1/2 tons of iron cuttings,19/ and 25 wagonloads of manure were put in the well. This operation took 3 months and cost the operator approximately $3,500. Descriptions were given of portable mud-mixing apparatus that could be moved from well to well. McGregor cited several wells where mudding had been effective in shutting off bottom water.

Naramore, just before his resignation from the California State Mining Bureau to accept the position of chief petroleum technologist, Federal Bureau of Mines, suggested a modification of the mud-fluid method to cope with conditions in the Sunset-Midway field. In a letter dated September 23, 1916, Naramore wrote to the State oil and gas supervisor (135, pp. 237-238) that in some parts of the field it had become difficult, if not impossible, to identify the top oil sand and it was impracticable to continue "the policy of protecting all oil sands with casing." In a specified well, Naramore stated that the hole should be drilled through the first flowing water sand and mud fluid circulated; then the well should be shut in at the surface and the mud fluid forced back into the water sand under a pressure of 700 pounds per square inch or more. A deeper water sand should be thoroughly mudded in the same manner and a tar sand, if found, should be mudded before cementing. "With formations thus mudded up, the very best possible results are to be expected with the cementing." Six hundred sacks of cement were specified to raise a solid concrete plug (outside the casing) well above the highest oil show. Naramore believed that the method as specified would keep water out of the oil sands and would prevent migration of any fluid in all sands so treated.

Bush (135, pp. 339-344) described the use of mud fluid in connection with abandonment of a number of wells and by means of graphic logs and other data showed the effectiveness of this method of building up an artificial body of clay around wells that would be impervious to water. Of particular interest is his description of a packing head for use in mudding wells. Compared with present-day wellhead equipment this device was a relatively crude assembly of material made in the field shops of an operating company. One feature that was to be developed by subsequent improvements was the side outlets and valves permitting pressure regulation. Bush stated that the packing head also could be used as a casinghead for high-pressure wells making large quantities of gas after the well is completed. (See section on Blowouts and Wild Wells.) One of these heads, which provided for movement of 6-1/4-inch casing within 8-1/4-inch casing while maintaining pressure between them, was made in the field machine shop at a cost of about $80.

The earnest efforts being made to reach sound conclusions as to the effectiveness of the mud-fluid method in oil-well operations - on trial in California fields in an effort to save casing where possible, which in early 1918 was "not the most plentiful thing in the world," to use the words of the State oil and gas supervisor - are evident in the complete record of a called meeting held in Los Angeles March 11, 1918 (136, pp. 77-109).

19/ Reference in the technical press to the salutary effects of adding weighting materials such as lead concentrates, iron oxide, barium compounds, and other heavy admixtures to mud fluids seems to have followed the 1914-19 period (177).

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After a paper by Nolan (136, pp. 77-79), in which he presented specific data to demonstrate the value of mud fluid in protecting oil sands, J. A. Pollard, who had written extensively on this method (155, 85) in 1913 and 1914 in collaboration with A. G. Heggem, offered his opinion that "the majority of drillers and operators are still in the dark as to the real action of the mud fluid in the ground." He then gave a blackboard talk to explain how mud fluid penetrates into various types of formations, quite in contrast with the plastering effect that some operators contended was caused by the "wobble of the rotary drill stem" (101). He cautioned that indiscriminate use of mud fluid in wells would ruin much good territory and stressed underground conservation - a subject which he said had received little attention in the industry.

He summarized his views on the use of mud fluid with a statement that "water in its own formation is not dangerous" and by keeping it there the damage done to nature by drilling a hole through a water-bearing stratum is overcome (121).

Bush (136, pp. 87-90) described the use of mud fluid in abandoning wells and cited examples in which thin mud had traveled 1,000 feet from one well to another. Another question that worried engineers pertained to the effect of mud fluid on cement. Stoner and Scharpenberg (136, pp. 90-97) found that different formations reacted differently to clear water, but to cement a well in the Lost Hills field successfully the drilling mud had to be removed from the sand face with clear water. The earlier writing of Arnold and Garfias (11) referred to proper conditioning of the hole before the cement was introduced into the well. Kirwan (136, pp. 100-109) described some interesting and effective measures employed to shut off water in the Salt Lake oil field (now an exclusive shopping district adjacent to Wilshire Boulevard in Hollywood, Calif., abandoned as an oil field in recent years because of its greater worth as real estate). After circulation was lost continually, Kirwan suggested that sawdust be added to the mud fluid. Later chopped hemp cordage (bullrope) also was used and the desired results were obtained. The use of such admixtures brings to mind the recent practice of adding cottonseed hulls and other fibrous materials to the circulating fluid to obtain similar results. The desirable condition of keeping sand out of the mud fluid also was stressed by Kirwan.

In a following chapter Collom (136, pp. 110-146) gave a comprehensive review, substantiated by many engineering data and testimony of drillers and others, comparing the various methods of excluding water from oil wells in California. He concluded that the source of fluid must be determined before remedial measures can be applied effectively and presented a table showing "conditions of hole necessary to determine source of fluid entering a well."

Water Analyses and Chemical Methods

The classification of oil-field waters on a chemical basis is traced to its beginning in the Water Resources (former Hydrographic) Branch of the Geological Survey 6 years before the presently considered period began. Stabler (175) first suggested the practice of expressing the results of water

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analyses in terms of "reacting values" in 1908 and followed this with a more detailed discussion in 1911 (176).

According to Reistle (158):

> Using this method as a basis and making some important additions to it, Palmer (152) applied the method in his work on the geochemical interpretation of water analyses, and it is now known as the Palmer system.

Washburne (185) discussed chlorides in oil-field waters in 1914; however, the primary thesis of his work was to show that waters associated with oil were widely different in composition from sea water of present geologic time. Rogers (162, 163) probably was the first scientist to apply the Palmer system in working out geochemical relations of oil, gas, and water.

Indicating that petroleum engineers were not remiss in using these scientific means of finding out all they could concerning petroleum reservoirs, Bell (136, pp. 367-369), referring to Rogers' work of 1917 (162), showed how the use of water analyses can be especially valuable in distinguishing between top and bottom water. He presented detailed chemical analyses of oil-well waters of the Casmalia field in San Luis Obispo County, Calif., determined by F. G. Tickell, then resident geologist for the Associated Oil Co. Bell explained in readily understandable terms the meaning of primary and secondary salinity and primary and secondary alkalinity and observed that "a few analyses costing about a hundred dollars may be the means of saving a string of casing costing several thousand dollars."

Another engineer who stressed the value of analyses of oil-field water was Neal (140), whose paper was discussed by such men as G. S. Rogers, previously cited, and R. van A. Mills, who, as a member of the Bureau of Mines, studied the chemistry of oil-field waters and developed a chemical process of excluding water from oil and gas wells. Mills filed an application for a patent on his process on October 15, 1918, under the Act of March 3, 1883, 22 Stat. L., 625, dedicating it to the public. The patent (128) was granted on July 4, 1922, and in later years the principles have been used in industry.

SHOOTING WELLS

The shooting of wells dates back to the patents of Roberts, applied for in 1864, and the "moonlighters" who shot wells at night to circumvent his patents (41); but according to descriptions of Kirwan (100), except for substituting 60 percent dynamite for "soup" (nitroglycerin), the methods used in California before 1918 did not differ radically from the early technique in which dynamite, cap, and fuse ("jack squibs") were dropped in the hole to detonate the explosive - with all too frequent disastrous results to equipment and "shooters." In fact, those unsatisfactory methods still were being used by some operators in 1916-17, although Illinois operators were using electrical firing devices in 1914 (189); however, Kirwan described the then recently improved method of molding blasting gelatin into torpedoes of different sizes for various wells and conditions and detonating the charge as desired and with comparative safety with an electric firing device.

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Advantages of the proper use of explosives in wells were reviewed by Kirwan after informing operators that blasting gelatin generates "1,300 volumes of gas under an initial pressure of 15 tons per square inch." He advised that frequently obstructions could be removed or defective casing side-tracked by shooting with less cost than by "fishing." Shooting to increase production was not prevalent in California because producing formations usually were soft, but in hard, close-grained strata Kirwan noted that shattering with explosives would allow fluid to enter the borehole more readily. Collom, reporting on the Santa Maria and adjacent fields, also recognized the effect of bore diameter upon production from shale zones of the district and suggested some means of increasing the open areas in the wells - such as careful shooting with dynamite - and subsequent use of screened liners to increase production.

Shooting was tried in the Kern River field as an aid in plugging wells but was not suitable because thin streaks of shale were interbedded with the sand. Accordingly, a method was devised for cutting the casing into lengths of about 5 feet; then a ripper was run in the hole. Ripping was started on the bottom length of casing and, when completed, the cable tools were run in; the ripped sections of pipe were then pounded down, clay and cement were put in and tamped, and in this way a solid plug was built up at the bottom of the hole.

In the Mid-Continent the use of very heavy shots of nitroglycerin in wells was recognized by some as poor practice. A writer in a May 1915 publication stated that shooting new wells in the Cushing field with heavy charges was "costly folly," as such procedure would tear large holes in the rock "where the water was stored under heavy pressure."

After Collom joined the Federal Bureau of Mines he described certain phenomena observed as pertaining to spontaneous explosions of nitroglycerin in wells in Texas (46) and briefly discussed shooting in his bulletin on prospecting and testing for oil and gas (47); but few, if any, careful engineering studies of the effects of shooting on increased production were reported in the technical press until Hill made some graphic analyses in 1925 (87).

COMPLETION AND OPERATION OF WELLS

The late H. C. George, in introducing his volume on completion and operation of wells (72), wrote:

> Only within the past decade has considerable attention been given to scientific methods of production of oil and gas.

Exceptions to any generalized statement usually can be found if the search is carried far enough, and the over-all correctness of George's statement in 1931 - dating scientific attention to the completion of wells as beginning about 1921 - is impugned in no way by reference to the few exceptions noted throughout this review of the 1914-19 period, more particularly those in the following paragraphs of this section.

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Kobbé (103) recognized a condition in 1917 that many operators persistently ignored to their later regret, namely, that "maximum recovery depends not alone upon efficient pumping methods but also upon the selection of a proper drilling system and the completion of a well* * *." He named five factors that should be considered in selecting a drilling method and specified the following:

1. Character of the formations overlying the reservoir.
2. Thickness of the oil-bearing stratum or strata.
3. Thickness and character of water or gas sands.
4. Expected gas pressure.
5. Total depth of well.

He believed that cable tools were best suited for drilling in wildcat territory, as at that time the method was peculiarly adapted to prospecting where accurate determinations of the oil-, water-, and gas-bearing strata were especially desirable. He quoted from Johnson and Huntly (96, pp. 118-119) to compare cable-tool and rotary systems of drilling, particularly as regards entering of oilbearing zones.

Kobbé also referred to the indiscriminate use of perforating machines in completing oil wells - a subject discussed in more detail by Arnold and Garfias (13), who in 1914 had reported on production methods used in California when wells did not flow naturally.

According to those writers, at one well (1,300 feet deep) in the Coalinga field, where the casing supposedly had been perforated three times, later inspection of the pulled casing showed that, except for a few holes, the machine had only dented the casing. Another difficulty developed in other wells, because the casing was so brittle that it broke out in large sections when the perforator was used or the collars of the pipe were strained by the perforator, causing subsequent collapse. The metallurgical skill applied to oil-industry pipe had not advanced to its present high point.

Kobbé described and showed pictures of different types of wire-wound and wireless screened casing, including the Layne & Bowler and McEvoy patterns. He believed that the main function of screened casing should be "the regulated entry of the maximum amount of sand and oil" to the exclusion of material that would interfere with action of the pump. This statement evoked considerable comment. In support of his view, Kobbe referred to the findings of Thompson (180) that in practice a screen of too fine mesh frequently decreased oil production.

It was not until a few years ago that engineers began to apply scientific methods to the selection of screen openings in oil strings (44, 154), and even more recently has this complex problem been attacked on a fundamental basis to determine, by laboratory procedure, pressure distribution in the space immediately surrounding slotted pipes. Miller (120) has found that there is a definite optimum size of opening that can be determined, with a fair degree of accuracy, to give maximum flow of oil into the well bore with minimum loss of pressure in the sand. However, in retrospect it should be remembered that the prevailing objective of 1917 was "more oil" and not minimum depletion of

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available reservoir energy, and Kobbé was attempting to solve a specific immediate problem of extracting as much oil as possible from unconsolidated sands in California by removing large quantities of sand with the oil.

Cleaning out wells was a subject also discussed by Kobbé. He referred to swabbing and the use of steam but thought that hot oil was best to "liven up" a well.

Interesting and valuable references brought forth in the discussion of Kobbé's paper were the works of Slichter (171) and King (99), but application of their scientific findings to oil-field production problems was not duly appreciated until some years later (110, pp. 12-15, 130).

Pumping

After a well ceased to flow naturally the customary procedure in many fields of the country was to tube it in preparation for pumping.20/ The polish rod, working through a stuffing box on the wellhead and constituting the upper part of the pump mechanism, was attached to the end of the walking beam with a suitable, or handy, connection. The source of power frequently was the steam engine used in drilling the well (or a gas engine replacing the original prime mover), connected to the bandwheel by a leather belt of several ply. Rubber-composition belts were used widely in the oil fields later as leather became more expensive; the technique of the rubber industry developed and the supply became more plentiful. Central powers had been used in some areas for years, but few of these were balanced by means of vector diagrams - unless a "resident engineer fresh out of college" was given the assignment of designing an efficient lay-out and staking the power site. Even then, terrain frequently had more influence with the production superintendent than the resolution of forces into their components in accordance with mathematical and mechanical principles known to Galileo (1564-1642).

Nevertheless, the advantages of individual pumping units and straight-line motion to the pump rods were recognized, at least by some manufacturers of equipment; because in June 1915 a nationally known equipment manufacturer carried a full-page advertisement in a trade publication calling attention to the advantages of individual pumping units equipped with a reciprocating device that gave the polish rod an "extra-straight-line motion."

About that time, also, a trade publication referred to an automatic pumping device operated by high-pressure gas or compressed air. The purpose was to have complete control over the gas- or air-head which actuated the deep-well sucker rods without manual control.

Those who have visited the Pennsylvania fields may be familiar with "air heads," popular before the World War period and still used on some properties. During the days of high-pressure (40 to 60 pounds per square inch) automobile tires, the unexpected release of air from one of these pumping heads usually caused the passing automobile driver, uninitiated in this method of pumping, to

20/ Usually the natural flow was through the oil string of casing because greater quantities of oil could be obtained in a short time in that way.

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stop his car and look for a blow-out. It appears that the idea of pumping wells by means of a vertical cylinder placed directly over the well, the piston of which is actuated by gas or air, is no recent innovation.

Air Lift

Miller (123, pp. 2-5) has given a concise historical review of the use of the air- (and gas-) lift method of flowing oil wells. These need not be repeated here except to mention his reference to the use of natural gas in lifting oil in the Cat Canyon field, Santa Barbara County, Calif., before 1911, which he believes was the first time natural gas had been used for that purpose. Augmenting Miller's interesting account of a general method of lifting fluid that antedates the petroleum industry, the present search of the literature has brought to light an account by A. F. L. Bell (133, pp. 231-232) of an experience of the Associated Oil Co. in 1909. The company installed large air compressors to handle water in the Kern River field, where water had migrated to the higher and shallower parts of the structure. Air was compressed to about 250 pounds per square inch and forced into shallow wells near the center of the dome. The wells were producing almost all water and a total of only about 150 barrels of oil per day. Soon production increased to over 2,000 barrels of oil per day. This output began to drop rapidly, but the area of water inundation was reduced greatly. The jets were removed, and the wells were returned to beam pumping because it was unprofitable to lift the heavy oil (about 14° A.P.I.) with air. In Bell's opinion it was profitable to handle such oil with air only when the wells produced 50 to 90 percent water.

Although the air- (gas-) lift method was well known, it was not developed extensively until "crooked"-hole pumping troubles and the need for lifting large quantities of fluid became evident about the time wells in the Seminole (Okla.) district ceased to flow naturally.

Stimulative Methods

Use of Vacuum

Various writers of 1914 and 1915 referred to the stimulative effects of "gas pumping" or use of (partial) vacuum. This is not surprising when it is known that Lindsly and Berwald (110, p. 4) found published reference to this means of increasing recovery of oil from sands in a treatise published in 1880 (40, pp. 260-262). The method was used quite generally in following years, especially in the eastern fields.

Washburne (187, p. 647), in discussing oil recovery, gave his view that "The vacuum method of pumping is undesirable because it does not create a high enough pressure gradient." Furthermore, he found that the vacuum method caused vaporization of the light gasoline fractions in the sand, which rendered "the little masses of oil more viscous and harder to move."

With decrease in pressure in the older portions of the Cushing (Okla.) field (Bartlesville sand, discovered in December 1913), some operators began to install vacuum pumps in June 1916 to draw more crude oil from the earth and to increase the quantity of casinghead gasoline (natural gasoline). The operators thought gas that would make 2 gallons of gasoline per thousand

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cubic feet was a "good grade which should yield a profit." Lindsy and Berwald give the histories of many properties to which a partial vacuum was applied during the 1914-19 period and discuss the effect on crude-oil production and natural-gasoline extraction.

Natural-Gasoline Extraction[21]

The natural-gasoline industry, then extracting a product called "natural-gas gasoline," was in its infancy. A paper by Burrell, Biddison, and Oberfell[22] describing extraction of liquid products from natural gas by absorbing the gasoline in oil, followed by distillation to drive off the liquefiable hydrocarbons, was mentioned in the trade papers of 1916 as an outstanding contribution.

Lindsly (109) also cited this paper and quoted costs of building a plant, as given by its authors, in briefly describing the absorption method of extracting gasoline. Compared with other known methods Lindsly stated that the absorption method gave greater recovery and plant and operating costs were lower. In addition, he described (by means of drawings) field and laboratory apparatus for making absorption tests to determine the quantity of gasoline extractable from samples of different natural gases, a subject of financial concern to producers of oil and casinghead gas.

Repressuring

Injection of Air and Gas

An unidentified writer in the Oil City Derrick of 1915 (143) referred to the practice of some operators in Pennsylvania, West Virginia, and Ohio, who were forcing air into the sand for the purpose of driving oil to other producing wells. It was rumored that production had been doubled or even quadrupled by this practice. Stimulation of gas production also was mentioned, the claim being made that air passing through the sand absorbed the lighter parts of petroleum and that in a few weeks enough gas could be obtained from the wells to run the gas engines used for pumping. The writer of the article believed that air injection was preferable " to the plan started by the Bradford producers of flooding the sand with water." (See section on Water Flooding.)

Several months later I. L. Dunn (60), owner of certain patents for injecting compressed gases into partly depleted oil sands to increase their yield, described the theory of the Smith-Dunn process, which he stated is based upon the compressibility of gases, the porosity of sands and the capilarity of oil sands. He gave some results that he had obtained with the process. Although early patents, one of them dating back to 1865, dealt with the placing of artificial pressure on an oil sand in wells (equipped with seed bags), those granted to Dunn in 1913 and 1914 were referred to in the press of 1916 as the first to state definitely that porosity of oil-bearing sand has a definite effect on production.[23]

21/ Kraemer (104) has discussed the beginnings of the natural-gasoline industry in more detail than is warranted in this section.

22/ Delivered before the Natural Gas Association of America, Pittsburgh, Pa., May 1916, later published in more detail as Bureau of Mines Bull. 120 (36).

23/ Johnson and Huntley (95) referred indirectly to this same aspect of oil production, namely, a "certain degree of fineness" of the sand was recognized as a controlling factor in recovery, but they gave no quantitative idea of the degree of fineness.

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Despite Dunn's success with his process the injection of gas or compressed air into oil sands to stimulate production was viewed with scepticism by many persons in the industry even as late as June 1916. According to reports in the press, application of the process to shallow sands in Ohio had been successful, but a recent test in Oklahoma resulted in financial losses "although the theoretical part of the work had turned out as expected." (144)

It remained for Lewis (106) to give the "industry the basic and studied report* * *which laid the groundwork for later research and extensive practical application of methods for recovering increased amounts of petroleum from underground reservoirs" (68, p. 5).

Water Flooding

Torrey (181, p. 146), writing on the history of water flooding, said, "There is little specific information as to how flooding originated" and referred to the "secret practice" of the method for more than 35 years until the Commonwealth of Pennsylvania passed an act (No. 322, approved May 17, 1921) legalizing the practice. Forest D. Dorn, president of the Forest Oil Co., Bradford, Pa., in an address entitled "A Brief History of the Origin and Development of Water Flooding" (unpublished), before a district meeting of the American Petroleum Institute held several years ago at Bradford, gave some additional sidelights. He quoted extensively from Carll (40) and showed that "water flooding was practiced, but unintentionally, for 6 years after the Drake well was drilled. Water was intentionally introduced in the center of the Pithole pool in 1865." However, Dorn said that flooding in the Bradford field began accidentally from old abandoned wells.

Lewis (106, pp. 92-117) has excellently described increasing recovery of oil by water displacement as practiced in 1917. Improvements such as the "5-spot" and delayed-drilling methods of flooding (forcing water into the producing sand through injection wells drilled in a definite pattern to be followed at a specified time by drilling a producing well in the center of the pattern) were to come at a period later than that covered by this review. They have been described by Fettke (65) and many other writers

Other Methods

Other methods of stimulating production were being tried. For example, electrical heaters to remove paraffin in wells could have had their inception in such devices as one reported in April 1915 to increase the oil flow in wells; however, the purpose of the electrical heater as used in California seems to have been to expand the gas in the oil-bearing stratum, "causing a greater upward pressure in the well."

The art of treating limestone formations with acid goes back at least to United States Patent 556,669 (granted to Herman Frasch on March 17, 1896). It does not appear, however, that this stimulative method was used to any extent until about the early 1930's (67, pp. 505-506), when it began to supplant to a considerable extent oil-well shooting as a means of increasing production. (See section on Well Shooting.)

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PETROLEUM RESERVOIRS

In an earlier section of this paper, citations show that one group (composed particularly of geologists) was concerned primarily with the genesis of petroleum, while others were interested in its accumulation. Still other technologists were beginning to direct discussion toward the physical characteristics of petroleum reservoirs - and sparingly to their behavior.

One of the first papers of this third class to be noted in reviewing the literature of the 1914-19 period is by Washburne (186), which he introduced by stating:

> Let us think of the geologic column not as a series of rocks but as a mass of irregular connecting capillaries. Different parts of the column may be distinguished by the absolute size and by the relative amount of its open spaces.

He then propounded certain principles of petroleum behavior as controlled by porosity of rock, average diameter of pores, and capillarity that must have been refreshingly original.

Unfortunately most "practical" operators of the period failed to appreciate their significance; for example, he pointed out that a natural oil emulsion could not exist in the rocks but was formed after "the final rush of the oil and water out of the rock pores into an open well." The truly practical application of this observation might have led to great savings for these so-called practical operators in reducing the cost of breaking emulsions formed by improper production methods.[24]

In discussing Washburne's paper, David T. Day revealed "the very considerable difference in solubility of natural gas in various oils." He stated that the old idea of stratified layers of water, oil, and gas in contact with each other "must be greatly modified because under the pressures existing (in the rocks), most of that natural gas must be in solution in the oil." He then referred to the action of a bottle of Vichy - now a time-honored comparison in which the term "soda pop" is used more frequently than Vichy.

Day made another significant statement: "Any change of pressure on that oil must affect the gas in solution in the oil, so the cause for the movement of oil, in migration, is, it seems to me, perfectly self contained. Any slight change of pressure or temperature will suffice to give plenty of reason for movement." Day evidently had distinctly in mind the principles of fluid and energy relations in oil-gas mixtures in the reservoir, even if they were vaguely expressed.

Other technical considerations of reservoir behavior were brought out in the discussion following Washburne's paper. An item that Washburne stressed, but which unfortunately was not followed, was the proper use of the term "rock pressure." He believed its use should be avoided in scientific discussions, except when the pressure exerted by the rock itself was intended, and suggested the preferable use of the term "closed pressure" to designate gas pressure in a well.

24/ See Shea, G. B., Practices and Methods of Preventing and Treating Crude Oil Emulsions. Bureau of Mines Bull. 417, 1939, 106 pp.; also section on Emulsions, this report.

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Others also considered subjects akin to present concepts of reservoir behavior during this period. For example, Ball (17) referred to the "radius which will be drained by a given well." Few data on these "radii of drainage" had been collected, but it was known that they varied between wide limits. Moreover, Ball cited testimony of W. W. Orcutt, a well-known operator in the Santa Maria and Los Angeles fields of California, who had found that wells in fields where he had operated had an effect that reached out into the sand body 1,000 and sometimes 2,000 feet. Orcutt also recognized a condition now referred to as a "pressure sink." He stated that the first man to complete a well in a new area would get the bulk of the oil and that the first well "loosens up the gas pressure" and that the line of least resistance is toward the first well. He cited as an example a well drilled in the Santa Maria field where the first well drilled on 80 acres had an extremely high pressure and produced virtually all of the recoverable oil, as other wells drilled in the tract later were "strippers."

Johnson (92) developed a hypothesis regarding connate water and its ultimate effect on oil production. In laboratory work he found that oil, gas, and water did not separate readily by "gravitational sorting while in a state of rest." However, if the apparatus was moved or shaken, separation occurred readily. He proceeded to state his observations and deductions that when oil, gas, and water move through a mass of porous material, the gas - because of its lack of capillary attraction - is retained in the larger pores. Also because oil has a greater viscosity and because the pores originally were water-wet, the oil would have more difficulty penetrating into the fine pores than water, and there would be "selective segregation" of the associated hydrocarbons in the larger pores. Johnson believed that later much of the connate water would be expelled from the reservoir in the direction of least pressure, which would be upward. Compaction and deposition of cementing material in the sandstone were given as plausible explanations for expulsion of the water from the petroleum reservoir.

Using his hypothesis of selective segregation, which has been sketched very lightly here, Johnson was of the opinion that large reserves of gas rather than oil were more likely to be found in deep horizons and that reserves of deep gas would be found not only in the then producing areas but in many others with apparently unfavorable structure.

This paper evoked considerable discussion, and communications from E. W. Shaw, Geological Survey, and C. W. Washburne, New York City, are particularly enlightening. Shaw pointed out that the conclusions of Johnson's paper (involving the "absence of water in deep sands") seemed unlikely on theoretical grounds and were not supported by field evidence. He said the need for work on sedimentary rocks was evident, as shown by a question recently asked him by "an eminent authority on economic geology," namely, "Is salt water at all common in oil fields?"

Washburne also questioned conclusions reached by Johnson because he felt that the general existence of large, deep reserves of natural gas could not be predicted from the available evidence. He thought that deep wells (4,000 feet in California) offered great promise of increasing fundamental knowledge on reservoir behavior - a subject that had received too little attention.

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Oil Left in the Sands (Estimating Reserves)

Washburne (187), in his paper before the American Institute of Mining Engineers in 1915, seems to have been among the first to give a studied public presentation of a scientific attempt to overcome the then existing difficulty (or impossibility) of estimating closely the obtainable quantity of oil underlying a given tract of land.

A fairly accurate reflection of a generally existing condition may be found in the observations of the previously mentioned anonymous writer in the Oil City Derrick (143). After admitting that producers could not be expected to operate their wells at a loss, he pointed out that they were giving little attention to the discovery of means for recovering all of the petroleum contained in the sands. The general practice seemed to be to obtain the quantity that could be extracted easily at the least expense in the shortest possible time and then abandon the wells. Some producers estimated that the quantity left in the rock was one-fourth to one-third of the original oil, and others thought the remaining oil was even greater.

This recording of an early estimate of recoverable oil on a percentage basis admittedly was conjectural, but Washburne (and other early estimators) also acknowledged the limitations of their methods. Reference was made to wells drilled in Pennsylvania fields within the past 2 years (1913-14) on leases that had produced for 30 to 40 years, in which oil was "discovered" that did not appear to have been disturbed by former drilling. The article deplored the fact that more concern was evidenced in obtaining large results from gusher territory than in experimenting with methods of thoroughly draining the sands of their store of oil "after the first head was off." The writer stated that money spent in experimentation to determine the quantity of oil that could be recovered from abandoned leases and the most economical methods of obtaining it would well repay the effort and probably would add large reserves to the known available oil in the ground.

In the absence of experimental data, Washburne arbitrarily estimated "relative saturation" (which he said depended mainly on the volumes of "free" gas and water "occluded in the oil or entangled in the oil-bearing layers") at 75 to 60 percent. His porosity estimates ranged from zero to 20 percent, and he used an extraction factor that ranged from 60 to about 80 percent. However, he recognized the horizontal as well as vertical changes of porosity in the same sand. He believed that outcrop samples would show porosity at least one-fourth too low because of the deposition of calcite. Although he acknowledged that his method had a probable error of about 50 percent, nevertheless it was based upon technical considerations, and he urged the practical importance of obtaining more data through studies of agencies such as the Geological Survey and the Bureau of Mines.

In discussing Washburne's paper, Roswell Johnson (187, p. 648) pointed out the difference between absolute and "effective" porosity - probably one of the first uses of the term. Johnson also recognized that extractability depends on the rate of loss of pressure. He said, "The extractability depends upon the pressure available for the exclusion (propulsion probably would have been a more expressive word) of the oil from the reservoir into the hole."

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Shortly after Johnson discussed Washburne's paper, he, in collaboration with Huntley (95), suggested a graphic method for estimating reserves and probably revealed certain facts regarding the behavior of wells and natural reservoirs that even now are not fully appreciated by many operators. Unfortunately, the popular title of their article may not have provoked the studied consideration that the text deserved. Despite the evident objective of creating a desire by the industry to establish fire-fighting stations to cope with wild wells that were becoming prevalent (see section on Blow-outs and Wild Wells), the article dealt with some fundamentals in reservoir behavior. These authors, after referring to the rapidly falling pressure in the North Cushing field, said in part:

> Now gas pressure in most pools is by far the biggest factor in the expulsion of oil from the sand. If gas pressure is very low no oil in paying quantities could be produced from any well whose sand has less than a certain degree of fineness[25/] without the aid of gas pumps (vacuum) or other unusual conditions such as encroaching water.

To illustrate their point they presented with their article a sketch illustrating the effect of the wasteful use of gas. The illustration was captioned "Production of a typical oil well: Curves showing relation of gas pressure to the extractability of oil content of a sand." Actually their sketch is a production-decline curve of a typical well in the Cushing field upon which a pressure-decline curve is superimposed. By blocking (cross-hatching) designated areas under the curves they calculated figures for total production resulting from a pressure drop from 600 pounds to 40 pounds per square inch. They assumed that 25 percent of the original oil could not be extracted; they evaluated the quantity of "flush" production, the decrease in production caused by continuous gas wastage on adjacent leases, and reached an estimate of the probable oil that would be produced from a typical well in the field.

In retrospect, it appears that several of the fundamentals suggested in that simple graph apparently were not recognized by a large majority of the "practical" oil men of the period - and by some of the technologists, also, because the same curve was reproduced, augmented by additional text, in Bacon and Hamor's treatise published a year later (16, p. 380).

In the next following issue of the same trade publication in which the graph first appeared there now may be found a certain amount of grim humor in a statement to the effect that not many years ago practical oil producers regarded the science of geology as a high-brow vagary; but, the comment continued, "Today (May 13, 1915) the geologist is regarded as a useful worker in the realm of oil. Large operators have much faith in the reports of their geologists and so do the small operators, all of which is a vindication of 'book larnin.'"

In September 1915 Lombardi (113) determined the cost of maintaining production in the Coalinga and Midway-Sunset fields of California. He did not use decline curves as now recognized, although he was definitely aware of the production-decline characteristics of "open-flow" wells. In this connection he said:

25/ See footnote 23.

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> It is well-known that new wells fall off in production as much as 50 percent in their first year, whereas wells 5 or 6 years old decrease very slightly in comparison.

From analyses of curves obtained by plotting the average daily production by months and using other pertinent data, Lombardi found for the Coalinga field that the cost of drilling new wells to maintain a constant rate of production for a given year was $40.38 per barrel of average daily production. A similar figure for the Midway-Sunset field was $33.70, and for all fields in California $38.00. Mark Requa, in discussing Lombardi's paper, stated that these figures were opportune as few people realized how much it costs to maintain oil production in the State.

Although Johnson and Huntley suggested the rudiments for estimating production from a well based upon a production-decline curve in May 1915, Arnold (8, pp. 707-711) later that same year realistically employed a somewhat similar type of production-decline curve in estimating future production from various States. He referred to the "theoretical curve of final decrease.

Pack (151) considered Arnold's curve with others in his careful review of known methods of estimating reserves. After calling attention to the shortcomings of the saturation method because so few factual data on sand thickness (and resulting total volume within the confines of the reservoir) porosity, and percentage of void spaces actually occupied by oil usually were available, he showed various types of production curves.

He then described the methods used by him and his associates (by means of curves) to show: (A) Field production in unit time, assuming that drilling maintains production (1) at constant rate and (2) at uniformly decreasing rate; and (B) field production expressed in terms of production per well per unit time.

Pack believed that estimates by his methods would be of the correct "order of magnitude," but he would claim no greater accuracy. His treatise showed the background of his work, first applied to California fields, but he advised his readers that the general method "might be applied to any field provided the necessary data are available."

Washburne commended Pack's work highly, stating that he had used similar curves, which he regretted could not be made public; however, he felt that "if any of the older companies would publish the decline of production on their leases, and if they would keep better records of the individual capacity of wells, it would be a boon to engineering science."

Secretary Franklin K. Lane, United States Department of the Interior, in his report for the fiscal year ended June 30, 1916, took cognizance of the quantity of recoverable oil left in sands by then used methods of extraction and stated that probably 50 percent of the original oil remained after wells were abandoned. However, Lewis and Beal (107), of the Bureau of Mines, did not present publicly their assembled data on a thorough study of the construction and use of what they termed "appraisal curves," until February 1918. The originating work was done by Lewis in 1915-16 while estimating future

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output of leases in the Osage Indian Reservation; and the curves and methods were developed further by Beal during 1916-17, assigned by the Bureau of Mines to gather and analyze data on the rate of decline of average wells in different oil fields throughout the country (22).

This forerunner of Beal's bulletin referred to the excellent paper by Pack (151) and discussed briefly the theories relating to the recovery of oil, expounded with such clarity in another report by Lewis (106). Methods commonly employed for estimating future production were reviewed; then the authors explained the derivation, construction, use, and accuracy of their curves, and suggested methods for making closer estimates. As far as determined, this paper was the first to suggest plotting a curve showing average production decline by means of logarithmic coordinates, from which a straight-line equation was obtained.

The factual material presented by Lewis and Beal showed that "on the average, wells of equal yield[26] will have approximately the same future productions, regardless of age of the wells."

In the opinion of E. W. Shaw, Federal Geological Survey, the work of Lewis and Beal would "outrank all other petroleum investigations except structural surveys." Future developments were to prove the uncontroverted truth of that statement.

At the same meeting at which Lewis and Beal gave their paper (A.I.M.E. meeting, February 1918) Requa (159), later appointed general director, Oil Division, United States Fuel Administration, presented tabular data and curves that were developed in connection with the valuation of lands, wells, and piping made by the Independent Oil Producers' Agency (California). Requa stated that an important step, following reconnaissance (during which all available data on each well were collected and an inventory made of the surface equipment) was to construct a curve for each district showing the decline of an ideal well from its beginning to exhaustion. The fields were represented by a family of average curves, each of which had only slightly different characteristics of decline. This striking similarity of average curves caused Shaw to call attention to the difference between those presented by Requa and those of Lewis and Beal. Shaw also suggested an approach to estimating reserves in "gassy" oil fields by means of comparing closed-in pressure decline and volume of oil produced, a method that previously had been treated in more detail by Shaw and his associates (167).

A valuable, practical suggestion to obtain information on the rates of decline of oil wells had been given in 1917 by Johnson and Bernard (94). Because the customary well-operating practice of that period was to flow the output from several wells into one or a few tanks for economic reasons, those writers suggested the individual gaging of each well in rotation - each well to produce into a special measuring tank for one day. Then the well flow would be switched into the general receiving tank until rotation order of the well again caused it to be gaged individually. In this way fairly accurate records of production from individual wells could be obtained at no great extra expense.

26/ Lewis and Beal were referring to wells in the same general area, producing from the same sand.

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Spacing Wells

No attempt has been made in this review to give a connected history of the growing realization that spacing wells on a tract of land overlying a natural petroleum reservoir is a factor to be considered in its behavior throughout its productive life - or perhaps more aptly and briefly stated, reservoir performance is a function of well density. However, a number of references have been found in the literature of the 1914-19 period that may augment those cited by Miller and Lindsly (125, pp. 1131-1147), Miller and Shea (126, pp. 351-363), Hardwicke (81), and many others who have written on the subject.

Some persons may think that close drilling was instituted in such fields as Santa Fe Springs and Signal Hill, Calif., or perhaps that Oklahoma City was one of the first fields with town-lot-drilling attributes. This is far from true; Triplett (184) used words of almost poetic imagery to show that "only the actors change"; the "pattern" remains much the same," and profit is the spearhead of the oil tradition from the Drake well to East Texas." Therefore, a detailed history of well spacing must begin with Oil Creek, Pa.

However, a well-spacing incident, with its humorous side, became "news" in February 1915. A trade paper called attention to action taken by the mayor of Lakewood, a Cleveland suburb, to regulate wells, both as to "location" and time of drilling, within the corporate limits of his municipality. The mayor was provoked because operators were not content to drill in the back yards of home owners, but some were even starting to drill in front yards, and during hours usually given over to sleep.

Wheeler (189, pp. 552-553) gave interesting information on the spacing of wells in the Illinois fields in 1914. The usual spacing was about one well to 5 acres in territory where the sand was fine-grained and 10 to 25 feet thick. This spacing assured "a slow decline and a reasonably long life. If the sand was thin or relatively deep the density was decreased - one well for 7 to 10 acres. Wheeler refers to overdrilling (1 well to 3 acres) that resulted in temporary large output followed by rapid decline, and the unwarranted cost of "a needless number of short-lived wells." His view was that town-lot wells seldom pay and that contractors and supplymen usually take the profits. However, he told of one extreme exception near Bridgeport, Ill. where 30 wells were drilled within an area of 2 acres, which in 2,190 days yielded 200,000 barrels. Assuming the over-all "pay" thickness to have been 80 feet (based upon Wheeler's information), the effective porosity 20 percent and the saturation 100 percent, the total voids in that thickness of sand of shallow depth underlying the 2 acres could contain only:

$$\frac{43{,}560 \times 2 \times 80 \times 0.20}{5.6} = 249{,}000 \text{ barrels (approx.)},$$

making no allowance for shrinkage.

The suggested "recovery" of 80 percent of the original oil, presumably accompanied by fairly large volumes of gas, from a 2-acre tract in 6 years, with eight of the wells still producing a total of 55 barrels a day at the end of the period, on first thought seems to be quite at variance with the

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findings of Muskat and his associates (131), reported in some detail by Miller and Shea (127). Actually, regional drainage rather than thickness of sand probably was responsible for much of the prolific production of this tract. Wheeler substantiates this view by showing that on many 40- and 80-acre tracts in the vicinity, after the line wells were drilled there was no need for drilling the inside locations because "the line wells will eventually drain the interior of the lease."

Huntley (91, pp. 21-25; 16, pp. 396-401) discussed at some length decline caused by drilling neighboring wells and remarked specifically:

> Town-lot development and the conditions brought about by many operators with small leases fighting for production result in extravagant and wasteful methods of production.* * * To drain an oil property most efficiently, that is, to extract all the oil possible with a minimum[27] number of wells and at an economical rate of production, it is essential to consider the best distance at which to space wells. This distance will, of course, differ for every producing stratum and for every field.

No engineer well versed in reservoir behavior could find fault with that statement, printed originally in September 1913.

Johnson (16, pp. 423-425) introduced his discussion of Spacing of Wells by referring to the Oklahoma situation (presumably the Cushing field), where "half a million dollars has been spent on unnecessary wells in 2 square miles." Truly, "only the actors change!"

The deputy supervisors of the California State Mining Bureau reported several difficulties originating from too intensive drilling campaigns and the close spacing of offset wells. For example, Naramore (134, pp. 134 and 140) described a "crowding campaign" by two companies in which four wells were drilled on each 10 acres in a checkerboarded tract. He summed this situation aptly (in its present-day application as well as to that of 1915-16) in the following statement:

> This section affords a splendid example of the uneconomical development and operation of oil land subdivided into small tracts, and especially when neighboring companies fail to establish mutual drilling restrictions. It is merely the culmination of the old-time method of being first to the oil, regardless of capital investment.

He also referred to keen drilling rivalry in a section causing the drilling of 20 new wells and the deepening of 6 others. Many of the offset wells were 300 feet apart, whereas on their own tracts the companies used a 500- to 700-foot spacing - frequently on a staggered pattern (93).

27/ A typographical error in Bacon and Hamor, vol. 1, 1st ed. (16), p. 399, makes this word read "maximum." The original printing in Bureau of Mines Technical Paper 51 (91), p. 23, is minimum.

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Bush (135, p. 337) also reported production practices in the Coalinga field that had "not reached as high an efficiency as is practicable." He referred particularly to one property where 34 wells were producing on 160 acres, an average of 4.7 acres per well.

Several public meetings were held during 1917-18 by the State oil and ga supervisor of California. One of these was for a discussion of proper and economical spacing of wells. Unfortunately the operators contributed few constructive suggestions, although the department of petroleum and gas presen some graphic data showing that in a certain tract in the Midway-Sunset field, containing four wells with spacings of 415 to 440 feet, there was a decided decrease in production from the tract as a whole as a result of the close drilling. It was thought likely that one of the wells flooded the oil-produci sand with water, but the evidence that each new well led to a marked decline in production of those previously drilled caused the State oil and gas supervisor to write: "The new well drew much of its production from areas previou supplying adjoining wells. As a matter of fact, one well, or at the utmost two, would have produced as much oil" (136, pp. 10-11).

It is significant that Requa and associates (159, pp. 537-539) gave considerable weight to spacing of wells in their appraisal work in California fields and constructed a chart to aid them. Their spacing chart allowed for depth and gravity of oil and indirectly recognized the influence of sand thickness on ultimate recovery.

Beal (22, pp. 43, 108-111, 130-131, 140, 161-162, and 164), in his more complete treatise of the subject of decline of oil wells, first presented by Lewis and Beal (107), frequently referred to the effect of well spacing on ultimate recovery; but it was not until after 1919 that Cutler, then an engineer of the Bureau of Mines, in collaboration with a valuation engineer of the Treatury Department, wrote specifically on "determination of proper spacing" (52).

In view of the subsequent frequent references in the literature and the courts to Cutler's Bulletin 228 (51) - especially to pages 85-90 on Well Spacing that have been reviewed so carefully by Miller and Higgins (124) - it may be of interest to quote the introductory sentences to that section of the Cutler and Clute report of 1921 dealing with well spacing, even though its publication came 1-1/2 years after the designated period of this review.

Cutler and Clute said in part:

> It may be desirable to an operator, from an economic standpoint, to produce and market all available oil at the earliest possible time, thus insuring the early return of expended capital for reinvestment. In small tracts this is often accomplished. There is, of course, a high immediate recovery when a tract is quickly drilled with closely spaced wells in the early life of the field. The wells are relatively large, their initial productions being high, due to unimpaired gas pressures. In such a case, with small tracts or town lots, close spacing is practiced.

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> Two close spacing is detrimental to the field as a whole, since the gas pressure falls off and its sustaining influence is lost to neighboring operators who might otherwise benefit from securing sustained production while their long drilling programs were in progress.* * *
>
> Only an agreement between operators regarding the spacing of wells can gain for the field the benefits to be derived from maintaining gas pressures, thereby securing sustained production for all properties concerned.

CONSERVATION

As a possible indication of the trend of thought of forward-looking persons regarding conservation at the beginning of the 1914-19 era, it may be significant that the first paper in the 1914 transactions of the American Institute of Mining Engineers dealing with petroleum discussed an oil-land law. According to Smith (172):

> . . . . The purpose of an oil-land law should be to promote development, with the aim of insuring the highest percentage of extraction at the lowest cost to the consumer and during the longest period consistent with fully meeting market demands.

He recognized this as a complex ideal because it included optimum recovery, minimum costs, and production responsive to the market to meet the practical ends desired by operators and public alike. He cautioned against provisions that would result in overproduction and waste. Ball (17), then chairman of the Oil Board of the Geological Survey, in discussing the existing placer laws as applied to petroleum, gave some enlightening figures regarding the industry at the beginning of 1914 and concluded that the placer law was unsatisfactory in most of its applications to petroleum because it was not in harmony with the concept of property relations in the United States; it forced line drilling, production in advance of demand, and serious waste of a valuable natural resource.

Waste in the petroleum industry and means of reducing it were not new subjects, as shown in earlier sections of this paper. In addition, the writer, in a section on Waste of Petroleum and Its Products in Geological Survey Circular 11 (174), has described early work of the Bureau of Mines as it pertained specifically to avoidance of such wastes. Much of the early endeavor to create a consciousness for the need of petroleum conservation originated in the Federal Geological Survey. Avery and Miller (15, pp. 1455-1462) have discussed in some detail, with general citations to historical background, the Survey's petroleum-conservation activities dating back to the meeting of the governors of the States in May 1908 upon the call of President Theodore Roosevelt. It will be recalled that reference has been made in an earlier section of this report to petroleum withdrawals (and restorations) of public lands and to the establishment in 1912 of Naval Petroleum Reserves 1 and 2 in California and 3 in Wyoming in 1915 (18).

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During the latter part of 1914 there was much agitation in Oklahoma because of the great waste of gas, particularly in the Cushing field, in conjunction with the production of oil. A prominent operator was quoted in the press to the effect that 200 million cubic feet of gas was being wasted daily and that the pressure (casinghead) was dropping 2 pounds a square inch each day. This wasteful blowing of gas to the air soon brought about a noticeable decline in the gas pressure in the northern part of the field, where drivers of automobiles were cautioned to extinguish their lights before traveling through certain low parts of the area. It may be remembered that at that time most automobiles were equipped with open lights of the acetylene or kerosene type.

It was stated that gas was being blown from the wells for two purposes: (1) To raise oil in large quantities to the surface, and (2) to relieve the pressure of the gas against the oil sand to prevent retarding the flow of oil out of the sands. A generally accepted practice at that time was to "blow the gas cap" for the intended purpose of inducing oil to migrate upward, where it could be produced through wells drilled high on the structure.

A correspondent to a trade publication, writing in April 1915, pointed out that the most insidious loss of gas was in permitting the gas sands to remain unsealed or uncased after the wells were drilled, "thus affording opportunity for the gas to escape into rock crevices or openings and become dissipated and lost without ever reaching the surface."[28] The statement was made that no gas well in Oklahoma had enjoyed a life of more than 2 or possibly 5 years because of criminal wastes, whereas if preventive measures were used the wells should last 15 to 20 years.

A group of oil and gas operators attempted to justify their methods and prove that they were not "outrageous ogres of waste" by citing A. Beeby Thompson, who in Petroleum Mining (London, 1910) had described the wastes of gas from the Baku (Russia) oil field. There, he had written, "20 to 30 million cubic feet of gas would be a low estimate for the gas that is daily wasted," and fuel consumed was 20 to 30 percent of the oil recovered by bailing. This group of Cushing operators probably considered an exaggeration the estimate made by their contemporary operator of 200 million cubic feet per day wasted from the Cushing field; however, the Federal Oil Conservation Board (64, p. 7), in reviewing the Cushing situation, found that at one period in the life of the field the average daily waste of gas was 300,000,000 cubic feet.

Whatever the actual figures may have been, they were high and could not be belittled, because Governor Cruce of Oklahoma, after observing the waste of oil and gas caused by excessive production without storage facilities for the oil and the escape of gas to the air, voiced his opinion that the State legislature should devote much study to the question of framing a law with the hope of conserving oil and gas in the ground.

Various remedies were suggested, andone group pointed out that the condition of gas waste could be remedied by the proper use of mud fluid. It was observed, however, that most of the operators were in a hurry to complete their wells and did not mud-off the gas-bearing horizon (presumably the Bartlesville sand).

28/ The view still prevailed in some circles that hydrocarbon fluids traveled in crevices in the rocks despite the fact that geologists had pointed out the structural and other conditions of the Bartlesville sand - the main gas-producing horizon in the Cushing field.

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An operator who had become gas-conscious suggested two methods of saving the gas: (1) Use a packer or set a string of casing at the top of the Bartlesville sand and (2) place separators at the mouth of the well. The packer or string of pipe, it was stated, was to prevent gas from escaping from behind the casing, and all gas from the Bartlesville sand would be diverted into the casing with the oil, thus reducing the loss 50 percent. By placing separators the oil could be marketed in the oil lines and the gas in the gas lines, affording an income from both to the producer. This operator referred to the process being used successfully in California fields.

Technologists of the Bureau of Mines were invited to discuss the technical side of conservation of oil and gas with representatives of the industry in Oklahoma and with State officials. They pointed out that much of the waste in the Cushing and adjacent fields was caused by improper drilling and casing programs and explained, with the aid of charts, a casing program and the use of mud fluid that would alleviate much of the trouble.

In 1915 the Director of the Bureau of Mines stated that wise legislation for the production of oil and gas resources should be drafted in such a way (30) as to

> Insure a market for natural gas and thus induce producers to conserve gas instead of allowing it to escape, a ratable marketing of all oil and natural gas offered for sale being provided for. In case production becomes too large for the available transportation and marketing facilities, then transportation facilities must be increased or the oil and gas must be confined until they can be utilized.

Nevertheless, there were many who severely criticized the Oklahoma Legislature for the passage of House Bill No. 168 on February 11, 1915 (6). It was termed "a weird system of regulation," and in March 1915 a trade publication disparagingly referred to the gas-conservation bill before the Oklahoma Senate. It was called a drastic measure along the lines of the oil-conservation act of the State passed a few weeks before. Provisions of the bill dealing with the conservation of gas that seemed particularly obnoxious to the editorial writer were the requirements that when gas was found the well must be capped until a market could be developed; water must be shut off under State supervision; and drilling through gas sands to oil horizons was strictly prohibited. If the pen of that editorial writer were taken as a medium for expressing the view of a fairly large group in the industry of that time, it would have to be concluded that the Cushing period was characterized by a general antipathy toward conservation precepts.

However, it is believed that a true cross section was not reflected by that one writer, because following Arnold's general review of the petroleum resources in the United States in 1915 (8), in which he touches upon their conservation aspects, he published a detailed paper in two parts entitled "Conservation of the Oil and Gas Resources of the Americas" (9). In concluding his thesis, Arnold, attributing part of his statement to Dr. C. W. Hayes, said:

> * * * * "utilization with a maximum efficiency and a minimum of loss" should actuate all who have the best interests of the oil industry of the Americas at heart.

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Again, present-day students of conservation should not forget the papers (part of a series on the mineral industries of the United States), the purpose of which was to analyze in nontechnical language the fuel situation in the United States, prepared and published by the Smithsonian Institution - that unique organization founded in 1846 "for the increase and diffusion of knowledge among men." Gilbert and Pogue (73), of the Division of Mineral Technology, treated the subject in wide scope as an economic study of a limited resource. The war situation was analyzed (73, pp. 35-39) as showing that "the latent weakness of the petroleum resource has become apparent under the influence of war stress." In summary, Gilbert and Pogue stated that the whole petroleum situation at that time was on an unusual basis and that betterment, "in the last analysis, depends upon the pressure of public opinion."

In 1918, also, Wyer (194) treated the subject of natural-gas conservation In a foreword, C. G. Gilbert, Curator of the Division of Mineral Technology, referred to the complex and critical problems pertaining to natural gas that required engineering and scientific treatment to solve. But as with petroleum, a "public opinion genuinely alive to the situation" was required to give the necessary stimulus to such technical pursuits.

Frey (70) has reviewed about 200 items of original-source material in tracing the conservation movement in the United States back to its colonial beginning, when settlers were concerned with protecting wild life, fish, and, to a smaller extent, forests in accordance with the need of the time. He follows this movement through various steps to the National Conservation Commission and its report in 1908 to President Theodore Roosevelt; then the establishment of the Bureau of Mines in 1910 and the revision of that agency's organic act in 1913 to include broader "scientific and technologic investigations" to conserve resources "through the prevention of waste"; and the Federal Oil Conservation Board, created by President Coolidge in 1924. He also treats later expressions of the evolution of the growing public interest in petroleum (69).

The details of Frey's review need not be repeated here, but it seems timely to call attention to one paper published in the technical press of 1916 that may not have been among the references used by Frey. The treatise of Ely (61), then professor of political economy, University of Wisconsin, developed a thesis "that a wise conservation policy means wise property relations a condition referred to by Ball (17) that the placer laws failed to meet.

The view of Ely briefly was that conservation includes two orders of inquiry, namely, the natural sciences and economics; and that in the second category, especially, certain features pertain to political science and sociology. This early recognition that seldom, if ever, is a technical proble met in industry that does not have surrounding economic and other human-relation boundaries and barriers recalls again the apt phrase used by Triplett, "only the actors change."

Although the period covered by this review actually ends with the close of 1919, many backward and several forward overlaps have been used to round out sectors of the cyclorama. This condition rests upon a statement quoted in the introduction, to the effect that the significance of newly found engineerin

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facts and resulting innovations in economic arrangements cannot be bounded by definite calendar limits. Therefore, the discussion would be incomplete without reference to the National Committee on Natural Gas Conservation.

This committee "was the result of a conference called by Secretary Lane on January 15, 1920, for the purpose of considering the natural-gas situation, which was growing acute, due to the depletion of supplies" (138).

The committee was composed of the Director of the Bureau of Mines, chariman, and well-known men and women representing industry, State and city public-service organizations, and home economics.

The 37 resolutions adopted by the committee dealt with utilization, transmission, and production of natural gas and covered virtually every item of economic and technical interest that seemed to pertain to natural-gas conservation. Many of the subjects were discussed in later Bureau of Mines publications (34) and in papers before the natural-gas industry.29/

Unit Operation

In discussing stimulative methods by which more oil might be extracted from the ground the anonymous writer in the Oil City Derrick, who already has been mentioned several times, early in 1915 (143) sensed the limitations of the gas-injection process because "* * *unless all lease owners in a given field joined in, those who did not would obtain the benefit from the installation of plants by others." In that brief comment, perhaps unknowingly, he enunciated the essence of the underlying thought of unit operation, although it was not recognized as such at the time. McMurray and Lewis (137) expressed more aptly the view that certain conditions of reservoir behavior cannot be controlled by surface property lines and that united action by the operators is essential. Part of their Bureau of Mines technical paper was copied in the trade press of October 1916, as follows:

> The maximum usefulness could be derived from a pool of oil or gas by it (the pool) being controlled by one competent management, as under such conditions it could be developed with the least waste and at the smallest cost. However, rarely is a pool under a central control; ordinarily a pool is divided among many owners. To get the best results the operators should act in unison for the protection of their common sources of supply and for their mutual benefit.

Others probably were thinking along the same general lines (15). However, it remained for Henry L. Doherty to formulate a specific plan of unit operation "which he first presented to the board of directors of the American Petroleum Institute in 1923 and made public in an address before the Petroleum Division of the A.I.M.E. at the Annual Meeting in 1925" (71). Thus, it is seen that most of the history of unitized control and operation of oil pools falls without the 1914-19 period, although the seed of an idea was planted, but not nurtured sufficiently, at least by 1915-16, and perhaps earlier.

29/ For organization and changing aspects of work of Natural Gas Association of America, see section on Petroleum and Natural-Gas Technical Societies.

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Storage of Natural Gas

Diminishing supplies of natural-gas fuel during and immediately after the 1914-19 period in urban areas of some of the Eastern States caused municipal authorities to look to technology for a solution of their problem. This condition is evidenced by the outgrowth of a Cooperative Fuel Survey instituted through a resolution adopted by the Council of the City of Buffalo, October 1920 (27).

The engineers who studied the fuel situation in Buffalo referred briefly to the storage of natural gas in the Zoar field about 30 miles south of Buffalo (27, pp. 65-66). Smith (173) has given a detailed account, based upon company records, of the gas-storage operations that began experimentally on June 15, 1916, when the wellhead pressure had dropped to 48 pounds per square inch. During the ensuing 9 years nearly 2 billion cubic feet of gas from other fields was injected during summer months and withdrawn during the peak-load winter seasons. At one time 300 million cubic feet was stored at a built-up pressure of about 215 pounds per square inch.

Panyity (153) in 1919 read a paper on natural-gas storage before the A.I.M.E. He described what he considered the favorable attributes of a gas-storage project and illustrated his paper with drawings to show how the input and producing wells might be equipped with packers to prevent the gas from escaping into formations, whence it could not be recovered.

Other storage projects were tried or contemplated in various sections of the country, but the major advance along this line of conserving natural gas to be used as needed seems to have been made about 1926, notably in Dominguez, Brea-Olinda, and other California fields (122, pp. 168-186).

TRANSPORTATION

Broadly speaking, the era of engineering design and mechanized pipe-line construction was far beyond the future horizon during the 1914-19 period in the history of the petroleum industry. As Cattell, Fowler, and Kraemer (41, p. 360) have staged:

> Looking backward to an earlier period (which might well have been stated: 1914-19), it is recalled that the "tong gang", making up a screw joint to the rhythmic beat of a hammer on the coupling, was a colorful picture of coordinated man power.

The "dresser" bolted coupling was advertised widely in the trade press and was being used on some natural-gas lines, but many were built with screwed joints. Welded lines did not become an important factor in natural-gas transportation until about 1926-27, although some short oil pipe lines were of welded construction before that time. Ditching, laying, and back-filling were done largely with manual labor. Westcott, even in the third (1920) edition of his Hand Book (188), in the chapter on Pipe-Line Construction, gives descriptions with the aid of several half-tone illustrations that would cause the present day "pipe liner" to smile reminiscently or with incredulity - depending on his experience. In fact, younger men might not recognize some of the terms. For example,

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Westcott gives the following personnel of a tong gang required for laying 8-inch pipe: 1 boss, 1 stabber, 2 jack men, 1 back-up man, 1 "dope" man, and 16 tong men. The interested reader is referred to Westcott's original writing for descriptions of the duties of each. A recent Bureau of Mines motion-picture film (33), by means of a "cut in", shows an authentic, unstaged picture of one of these gangs in action contrasted with present-day mechanical equipment and welding paraphernalia.30/

Nevertheless, deterioration of pipe lines by corrosion after being laid is not new, and protective means have been used for many years. An item in a trade publication of March 1915 states that pipe lines in the western United States (presumably California) frequently ran into alkali soil which corroded the pipe. Asphaltum paint had not been particularly successful, but bitumen enamels put on fairly thick had resulted in some successful protection. In the experience of an observer of that period, the most successful method of protection was use of especially prepared roofing paper, applied either in a spiral wrap or with a longitudinal lapped seam. The pipe couplings or collars were protected by building up shoulders and "doping them with hot stuff" (painting them with a heated, tarlike compound).

Pipe-line companies in the Gulf-Coast area also were experiencing troubles because of corrosion of their pipe lines. In 1916 the Rio Bravo Oil Co. supported a 4-inch line across a salt-water marsh on wood brackets treated with creosote and covered the pipe with concrete.

For several years both the American Gas Association and the American Petroleum Institute have sponsored research that has resulted in splendid, published treatises on the corrosion of pipe lines by acid and alkali soils and electrolysis (62, 111). The study of stray currents, however, is not of recent inception. Prof. Albert F. Ganz, Stevens Institute, in September 1916 was studying stray currents in pipe lines with the view of finding where currents leave trolley lines and cause electrolysis and the subsequent pitting of metal pipes in the ground. The remedy then was to insulate the pipes (for example, dielectric fiber gaskets and thimbles were used to separate flange connections), and the rails of electric trolley lines were bonded to prevent currents from entering, traveling through, and leaving adjacent pipe lines.

There was much less likelihood of gas hydrates forming in natural-gas transmission lines (55) than under present operating pressures and temperatures, and it is not likely that this phenomenon was recognized by pipe-line companies transporting natural gas in 1914. The presence of water vapor in the gas and its detrimental effects on lines, meters, and regulators because of freezing were reported by Wyer (193).

To be treated adequately, the story of natural-gas transportation and measurement would require many more pages than can be allotted in this review. It should be noted, however, that orifice meters were being used in 1916 and that the Westcott meter had been equipped with a self-draining attachment that permitted it to be used in measuring casinghead gas either under pressure or vacuum.

30/ A sound version of this film has been prepared (May 1941).

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MISCELLANEOUS TECHNICAL ADVANCES

Evaporation Losses

The Bureau of Mines was instrumental in calling attention of the industry to incorrect methods of storing petroleum, through the initial engineering work of Wiggins and associates (191), who, because of a threatening shortage of gasoline in 1919, were authorized to study conditions in Mid-Continent fields where there was only general knowledge regarding evaporation losses. Wiggins estimated that in 1919, during storage of crude oil on leases in that area, the quantity of petroleum vapors going to the air was equivalent to about 3 million barrels of gasoline - about 1.5 percent for lease storage alone. This was only part of the loss, as shown by Schmidt (164) in a tabulation giving the results of a 1920-21 survey made by the Bureau of Mines. The average over-all evaporation loss of crude petroleum in the Mid-Continent field from well to refinery was 6.2 percent of the gross production at that time.

Wiggins also pointed out in Bulletin 200 that the light ("gasoline") fractions in crude oil evaporate "from one-half to six-tenths as rapidly as the same gasoline after being distilled and stored, all evaporation conditions being the same."

It must not be supposed that individuals and some companies were unaware or unmindful of these losses from evaporation before the Bureau's work. For example, in 1914 W. W. Orcutt, well known for his development of the Santa Maria and other fields in California, referred to the storage of oil in open reservoirs that in 5 months caused a 50-percent loss of the most valuable fractions.

Wheeler (189, p. 555) told of wood tanks being used in the Illinois fields in 1914 that were housed in frame structures to reduce losses from evaporation during summer months; and in November 1916 trade publications carried advertisements of a patented process for hermetically sealing tanks to reduce "to a minimum the possibilities of loss of oil by fire or evaporation." Although the Bureau of Mines did not report its tests on light-color tanks until 1925 (164), suggestions were made through the press in 1915 that white paint on tanks keeps them cooler, hence evaporation is less. It was stated that one large company had been using white-painted storage tanks for years.

Despite these exceptions, knowledge of causes of evporation and leakage losses and of means of prevention was scanty in the1914-19 period as evidenced by dark-color (even black) tanks and open or exposed storage, which were common. Bradley (25, 26) reported that there were no "absolutely air-tight coverings over steel tanks in the Mid-Continent field" and referred to the building of steel tanks under emergency conditions in rapidly developing oil fields. Contractors often were rushed to complete a job, with the result that the workmanship was not first-class.

To Bradley's knowledge only one attempt was made to determine losses from earthen storage reservoirs in the Cushing (Okla.) field. The loss from 35,000 barrels of crude oil stored for 52 days was approximately 18 percent.

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Some concrete storage reservoirs were being used, and engineers gave careful consideration to structural design to prevent leakage through cracks that might be caused by settling or shrinkage (23). However, the more insidious loss of valuable volatile products through the roof was not always appreciated. About this time a trade publication gave considerable space to the description of an 800,000 barrel concrete reservoir, stating that the roof area was large enough to contain a baseball diamond. A picture accompanied the article which showed the roof area equipped with large ventilators of the louver-type - permitting the lighter hydrocarbon gases to escape into the air. This reservoir was built to serve an oil field in a semitropical climate, where evaporation losses would be high under the best conditions.

Emulsions

Antedating by several years research on oil emulsions that was to reduce appreciably losses caused by "cut oil,"[31] Wheeler (189, p. 555) in 1914 called attention to "B.S.," which he described as the emulsion of oil, water, air, and sediment formed by improper pumping. In the Illinois fields, as well as in other producing areas, it was (and in some fields still is) common practice to have special sludge pits near the lease tanks where emulsified oil was (is) burned wastefully. Wheeler observed that if the services of a capable chemist were retained, virtually all of the B. S. could be recovered as good oil.

Hardison (80) told engineers in 1915 that the technical literature of the oil industry pertaining to the separation of oil and water, as well as to other technical subjects, was extremely limited and unsatisfactory. For that reason it was necessary to experiment to find a suitable method for treating emulsions by the application of heat. He described experimental plants that he had built and gave data on one that seemed to meet the needs of his company. Bureau of Mines Bulletin 250 (58) contains a selected bibliography on oil-field emulsions. Some of the references - especially the patents - fall within the 1914-19 period, but most of the technical writings were published after 1920. According to Shea (168), "* * *in recent years there has been a growing realization of the importance of emulsion-preventive measures," whereas formerly the emphasis seems to have been on finding ways of "breaking" them after they were formed.

Carbon Black

Carbon-black production is a manufacturing process, but it is associated intimately with natural-gas production and utilization. Accordingly, a brief section is included in this paper. Neal (141, pp. 3-5) summarized the early history of the carbon-black industry, and more recently Allen and associates (1) have written an interesting historical account in which they show that soot in various forms has been known and used "since the beginning of time" (measuring man's strivings - not geologic epochs). It appears that carbon black made by burning gas was manufactured first in 1864 by J. K. Wright, a

31/ Dow (58, pp. 3-4) cites F. M. Seibert, chief chemist, Gulf Producing Co., who "estimated that in 1920 and 1921, 100,000,000 barrels of cut (emulsified) oil was produced in the Mid-Continent and Gulf Coast fields and only half was successfully treated." In California (1922) more than 10 percent of the production was emulsified.

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Philadelphia ink manufacturer. The price at that time was $3 to $5 a pound. Consequently its use was restricted. At the beginning of the 20th century the daily output was about 20,000 pounds and the price was about 6 cents a pound.

Quoting from the cited work:

> In 1915, on account of the World War, the price of zinc oxide went so high as to make its use prohibitive in rubber compounds. It was then that rubber chemists instituted a search for other compound ingredients that might be used in the manufacture of rubber products, principally tires, and it was then that the field of carbon black as a pigment of rubber was discovered. An English company is given credit for first ascertaining this valuable property, and jealously guarded their secret by buying their carbon-black requirements through a chemical company.

An American manufacturer announced a black tire during 1915, and the bla Silvertown cord appeared in 1916. Rapid building of plants followed, particularly in West Virginia and Louisiana, with prices of carbon black going to 20 cents per pound or higher. However, not until 1919 did the increasing demand for information on carbon black reach a point that justified the Geological Survey in beginning to compile annual statistics on this natural-gas product (170). The statistics for 1919 were published with those of 1920, when Sievers found a 1.4-percent decrease in total output from 52 million pounds for the previous year. Moreover, 36 plants were operating in 1919, compared with 35 in 1920.

He explained this slight recession in activity by referring to war demand. Presumably the inertia caused by that stimulus kept the plants "operating at or near full capacity" through 1919, but, according to Sievers, "since normal conditions have been restored the production has decreased." However, in 1921 the total production jumped to nearly 60 million pounds, as a result of increased demands of the rubber-tire industry.

West Virginia was far in the lead with plants and quantity in 1919. Louisiana was a poor second, with only one-third the number of plants and less than half the production. In 1922 Louisiana increased its production 67 percent and became the leading State - an evidence of the migratory tendency of this supplementary industry to build plants where gas supplies are large and the cost of gas is low. However, Oklahoma never utilized large quantities of its waste gas in this way. Texas did not enter this field until 1923, with several plants in the Breckenridge area; but with the opening of the Texas Panhandle gas field most of the "black" operations of the State centered there. (See section on Physical Landmarks, Texas Panhandle.)

Safety in the Petroleum Industry

A correct appraisal of the growth of safety consciousness in the petroleum industry would entail search of existing literature and subsequent writing far beyong the scope of this paper. Preventing accidents to workmen and to users of petroleum products is interwoven so inextricably with the mechanical

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business of extracting crude oil and natural gas, transporting them, and manufacturing and distributing their products for final use, that the pattern of one cannot be traced without finding the other superimposed upon it. For example, correct structural design, construction, and guying of derricks (see section on Derricks and Derrick Safety) have as much significance in the saving of lives of workmen as in the successful completion of wells, because in the final analysis no well can be judged completed successfully that has caused injury or death to those working on the derrick floor, in the derrick, or adjacent to it. A few observations may make this point clearer and show that the seed had actually been planted, even if the roots of a strong growth had not sprung from that seed during 1914-19.

Many oil companies probably looked upon their safety activities at that time through the eyes of their claim adjusters rather than through those of their infant engineering departments, but it would be wrong to assert that the viewpoint was prevailingly fatalistic, as expressed by one operator at a somewhat later date: "Accidents just happen. Nothing can be done about them."

It is well known that the Bureau of Mines was created "to promote safety and efficiency in the mineral industries," and although mine disasters may have been the major reason back of its organization, petroleum safety was not neglected. The reader may recall that the Bureau issued a technical paper in 1914 explaining the safe use of electric lights at oil and gas wells (42). In 1913 Clement showed the influence of inert gases on inflammable gaseous mixtures (43), and other early publications of the Bureau gave scientific facts regarding the inflammability and explosibility of mixtures of petroleum gases and air.

In 1913 more than 1,000 persons were burned to death and 3,000 persons were injured in the United States because they were unaware of the great danger attending the handling of gasoline. Gasoline was strained through chamois skins to remove water and other impurities, and many fires resulted therefrom. Stoddard solvent was unknown as a cleaning fluid, and the washing of silk clothing in a bucket of gasoline was practiced commonly by housewives and resulted in many tragedies from ignition by static electricity. Little was known by the public about the explosive qualities of hydrocarbon vapors given off by gasoline mixed with air. To overcome this condition Burrell (35) wrote and the Bureau of Mines published a technical paper on the hazards of handling gasoline. He showed that 1 gallon of gasoline when vaporized will produce about 32 cubic feet of vapor (under atmospheric conditions). With a lower explosive range of 1.4 percent by volume (upper range about 6 percent), 1 gallon of gasoline under ideal conditions would "render 2,100 cubic feet of air explosive." (See later work by Coward and Jones (49)).

Reference has been made to the pioneering work of Bureau of Mines engineers in 1913 in devising safe means of drilling wells through workable coal beds (160), and in 1918 a bulletin on oil and gas fires was published (24). Other subjects studied were carbon monoxide hazards (37) and protection against poisonous vapors by means of gas masks - an industrial outgrowth of the Bureau's war work (32).

In 1923, the Bureau definitely assigned petroleum engineers to devote full-time study to technical considerations of accident prevention. They have

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worked closely with oil-company safety engineers and officials in bringing about a better realization that "Accidents can be prevented" and that "Safety pays its own way."

CONCLUDING STATEMENT

In making the foregoing review and digest there has been no pretense to cover all developments in the departments of exploration, drilling, production, transportation, and related activities of the American petroleum industry between 1914 and 1919. An untold number of volumes, with a myriad of citations to other background material, have been published on the subjects discussed in this report. Many subjects not treated hold equal importance with those listed in the contents.

For example, studies of earth temperatures recorded in wells, as conducted by Van Orstrand (149) and associates, go back many years, although only recently has their important bearing on practical problems of oil production been generally recognized. In 1916 Johnson (16, pp. 422-423) thought that the outlook for the successful use of geothermic methods was not very promising. It would be difficult - if not impossible - to mark where research of this type reaches out from pure science into the field of practical application. Many evolutionary developments resulting from work by members of the Federal Geological Survey, State geological surveys, and other agencies have been omitted, not because there has been failure to recognize their value but because the field is too broad to cover in this paper. Wherever possible emphasis has been on the engineering side, with recognized exceptions throughout the report.

The scope of this review could be widened almost without limit, as the following incomplete bibliography attests. Still more revealing are the over-all contents of the several bibliographies of the Bureau of Mines on petroleum and allied substances (38), beginning in 1915 and extending through the 5 years under consideration. These include the 1920 references because the bibliographies for 1919 and 1920 were printed in one volume with no separation on a yearly basis. The following table shows the total number of references in each of the Bureau of Mines bulletins, Bibliography of Petroleum and Allied Substances, 1915 through 1920.

Bull. No.	Year covered	Total number of bibliographic items
149	1915	1,455
165	1916	1,357
180	1917	1,489
189	1918	1,725
216	1919-20	4,532
Total	1915-20	10,558

Some of these items were duplicated in different publications reviewed by the abstractors, and there were other circumstances causing overlap. Moreover, many of the references to books, periodicals, society transactions, patents, and other citations covered subjects not included in the title scope of this review and digest or that of Kraemer (104) on refining technology for the same period. Nevertheless, the gradually expanding volume of

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printed material and breadth of subject material through the years (during which essentially the same abstracting procedure was followed) show a definite trend toward greater and wider distribution of knowledge on petroleum subjects. Moreover, the printed material having real technical significance seems to have become increasingly predominant in the later bibliographies.

Careful study of the gathered material in this digest fails to reveal a discernible break in the trend of cumulative knowledge caused by active entrance of this country into the war. Although the evidence does not justify a categorical statement, the present study - as reflected by short glimpses and thumb-nail sketches of specimen contributions to the fund of knowledge of scientific subjects pertaining to finding, extracting, and transporting petroleum and natural gas - suggests that a mental awakening was taking place between 1914 and 1919. Actually, this urge may have begun a few years earlier. The minds of men and women were turning more and more to the possibilities and means of determining through research and field investigation the working of physical and chemical laws in nature. Refinements - sometimes leading to modified concepts of fundamental behavior - and the best practical applications of this newer order remained for a later period, not covered by this paper, when the industry and the country were not so concerned with the urge "more oil!". Standing alone, the petroleum-conservation aspects from 1914 to 1919 have many anomalous peculiarities because so much was known about petroleum behavior and so little was done to profit by this knowledge.

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